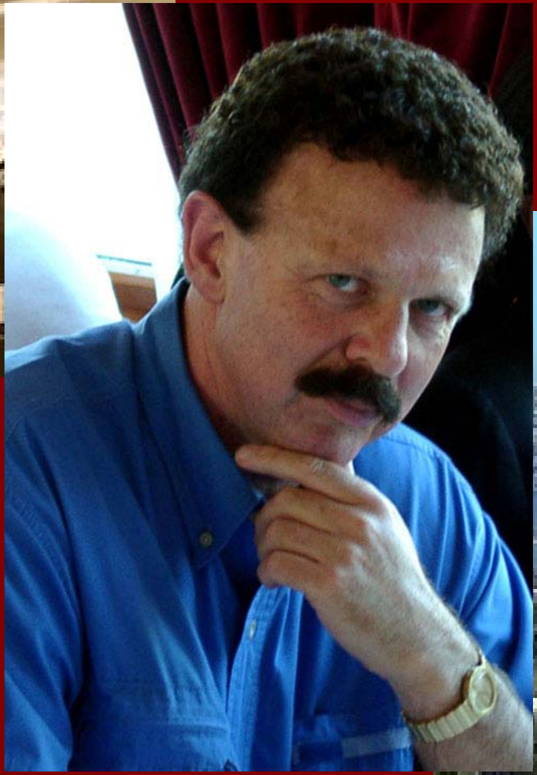



HUMPTY DUMPTY HAD A GREAT FALL.
HORSES
KING'S MEN
TOGETHER AGAIN!
SAT ON A WALL
KING'S MEN
TOGETHER AGAIN!
A WALL
FALL.

*NANO*HIGH LECTURE SERIES*
Lawrence Berkeley National Laboratory, April 24, 2004

Micromachines

Robert O. Ritchie

Materials Sciences Division, Lawrence Berkeley National Laboratory,
and Professor of Materials Science and Engineering
University of California, Berkeley

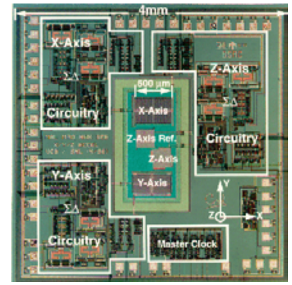
with particular thanks to

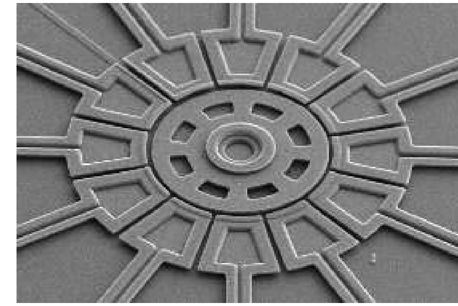
D. H. Alsem, C. L. Muhlstein *(Penn State)* and **E. A. Stach** *(NCEM)*

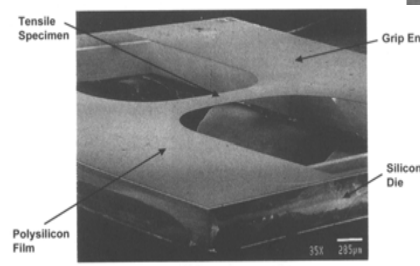
Based on work supported by the U.S. Department of Energy (Basic Energy Sciences), NEDO and Exponent, Inc.

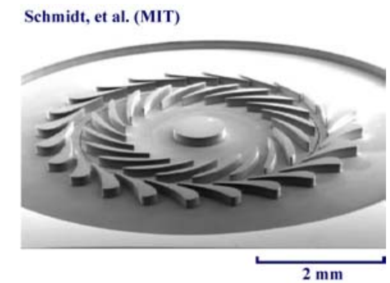
Outline

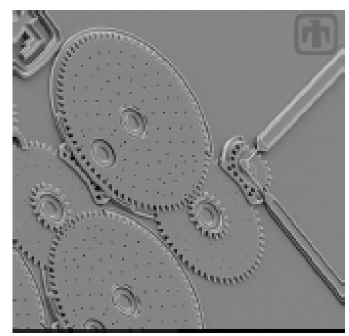
- What are micromachines (MEMS)?
- How are they made?
- What are they used for?
- How we use MEMS in research
- To find out how things break!
- The future – nanomachines!

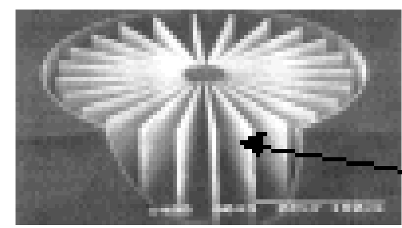


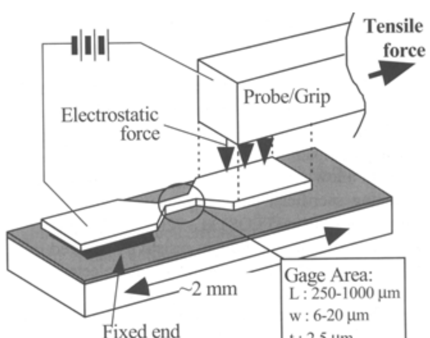


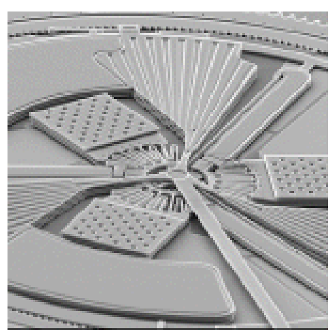


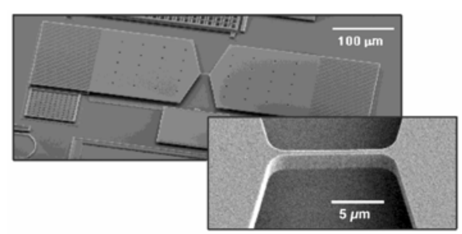


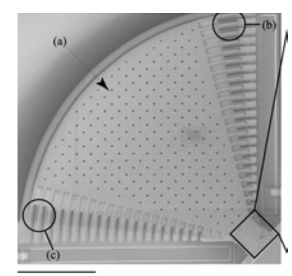




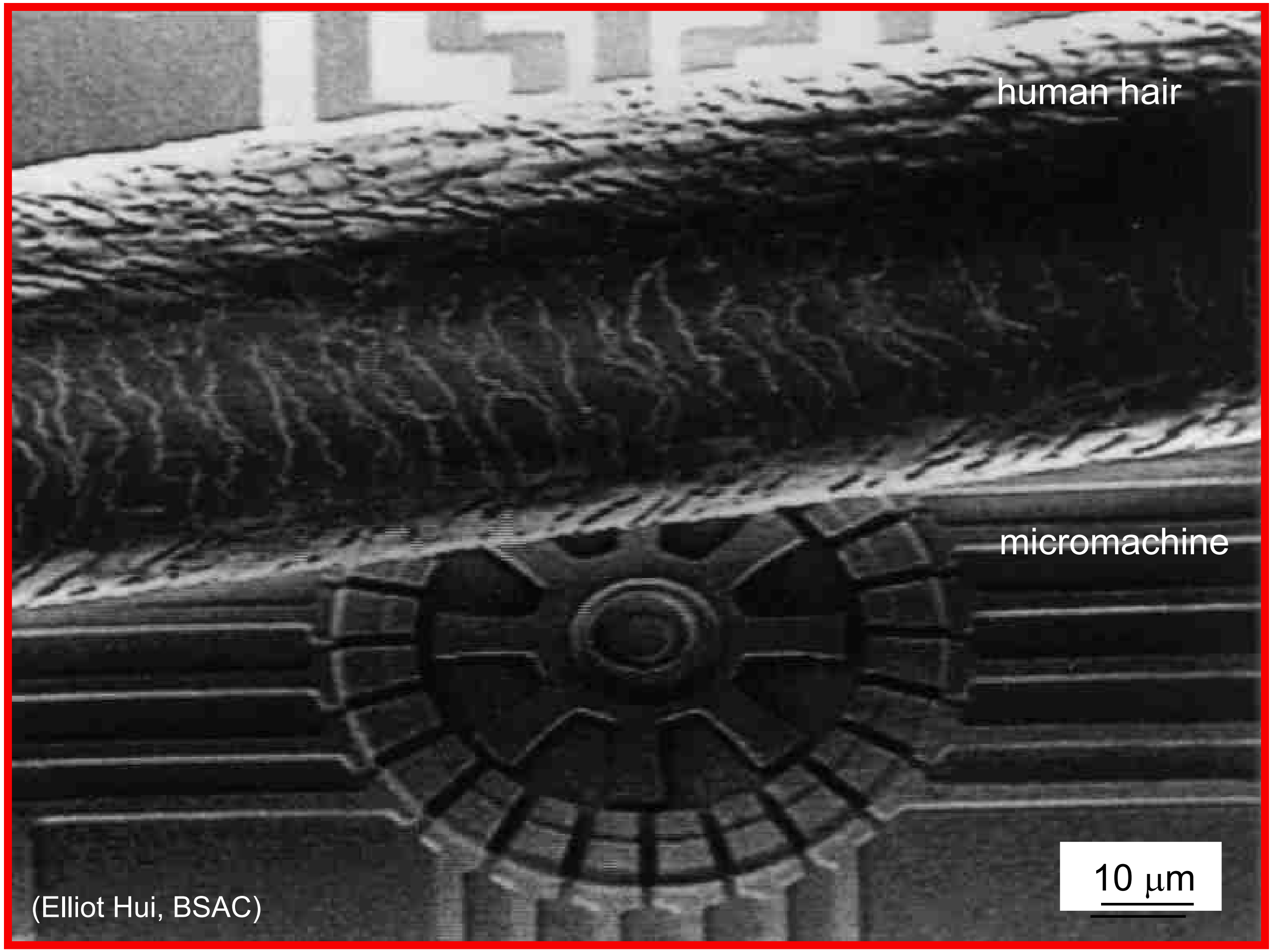








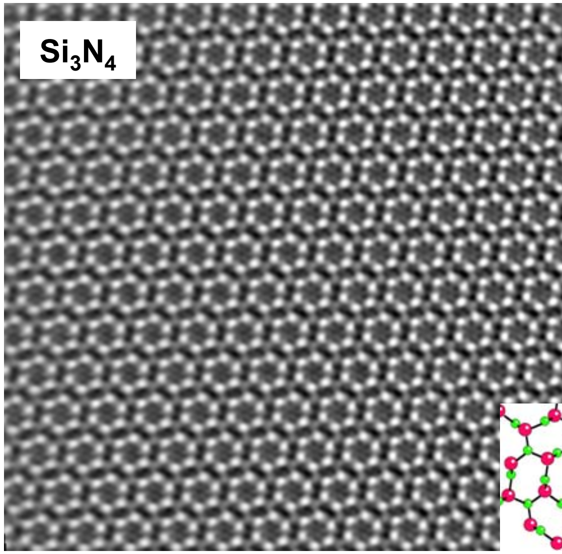
Exactly How Small is Small Here?



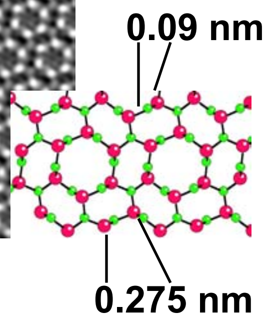
- The dimensions of current micro-machines (MEMS) are on the order of micrometers (microns – μm), i.e., millionths of a meter
- next generation machines (NEMS) may be on the order of tens to hundreds of nanometers (nm), i.e., nearly a trillionth of a meter!

- a silicon MEMS micromotor next to a strand of human hair
- the diameter of the hair is about 50 μm (50,000 nm!)

Length Scales in Material Behavior



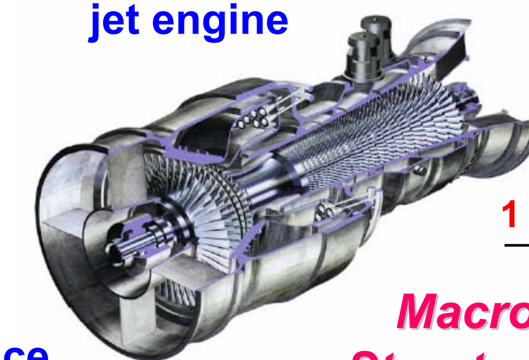
ceramic crystal 0.1 nm



Atomic structure

sub-nanometer
($<10^{-10}$ m)

jet engine



1 m

prosthetic device

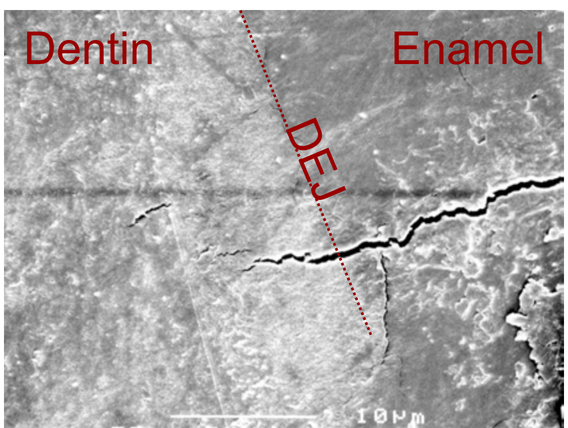
10 mm

Macro Structures

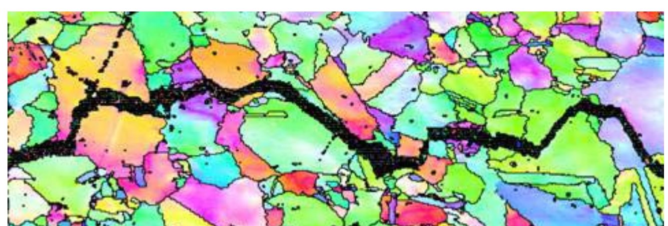
cm to m
(10^{-2} to 1 m)

Microstructures

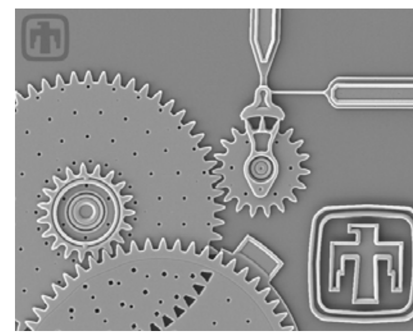
micrometers
($\sim10^{-3}$ m)



crack in a human tooth 1 μm



crack in a Ni alloy blade 10 μm



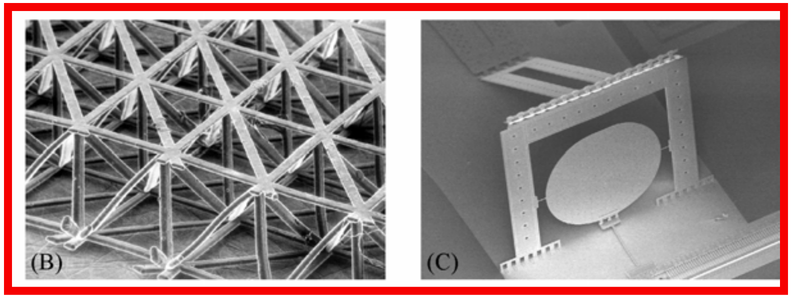
micromachines 10 μm

Why Miniaturization?

- **Why miniaturization of machines?**
  - smaller devices (portability)
  - low power consumption
  - very inexpensive when mass produced
  - because we can……..

“They may or may not be useful, but they surely would be fun to make.”
(Richard Feynman in ‘*There’s Plenty Of Room Near The Bottom*’, 1959)

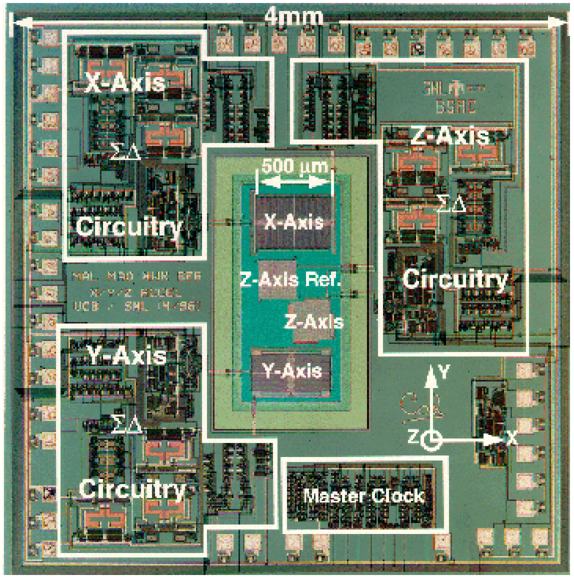
- **Main materials used:**
  - polycrystalline and single-crystal silicon
  - silicia (SiO_2)
  - silicon nitride (Si_3N_4)
  - silicon carbide (SiC)
  - diamond-like carbon (DLC)



5 μm

What are Micromachines?

- **Micromachines are known as MEMS**
  - **m**icro-**e**lectro-**m**echanical-**s**ystems
  - many applications are used today
    - inertial sensors (e.g., in air bags)
    - medical devices
    - memory and mass storage
    - micro-mirrors for digital projection
  - not to mention future applications
    - “pocket turbines” (to power the soldier of the future!)

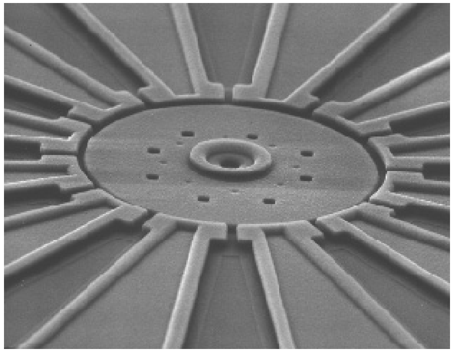


Analog Devices air bag sensor

- **Next generation of machines may even be smaller - NEMS**
  - **n**ano-**e**lectro-**m**echanical-**s**ystems

Some Definitions

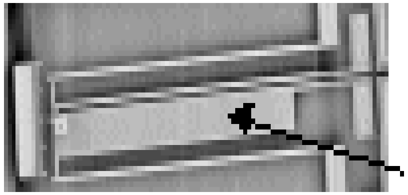
- **MEMS:** a miniaturized device or array of devices consisting of electrical and mechanical components that is fabricated using integrated circuit (IC) batch processing techniques



100 μm diameter wobble motor

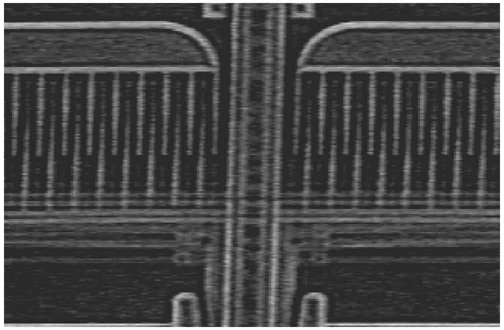
from M. A. Michalicek, Un. Colorado

- **Sensor:** a device that “senses” useful information from its environment and provides output to a measuring instrument



inertial sensor for passive restraint system

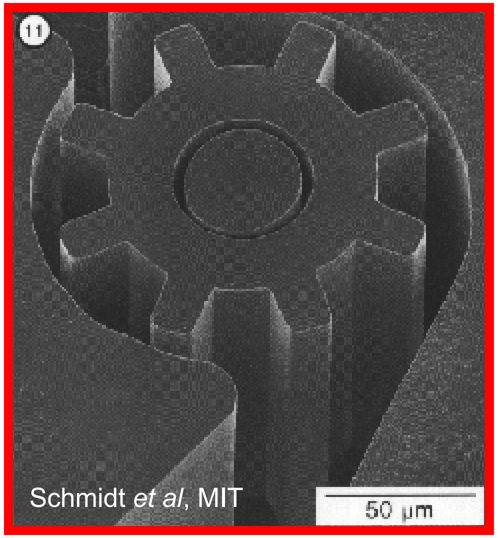
- **Actuator:** a device that can generate a force to manipulate itself, or other devices, to perform some function



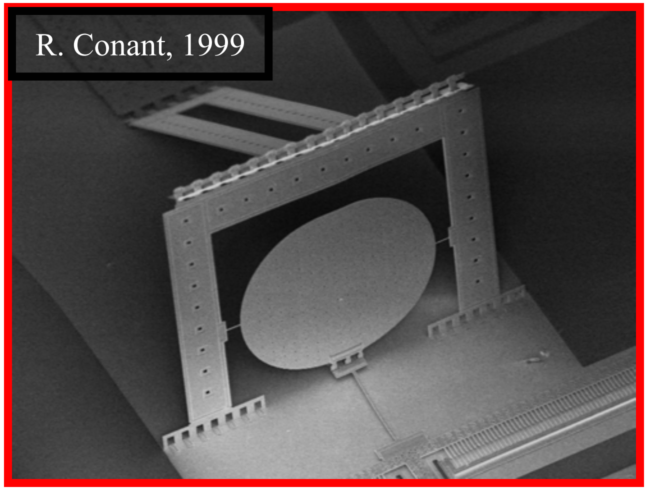
electrostatic motor (“comb drives”)

from D-H. Alsem, UCB

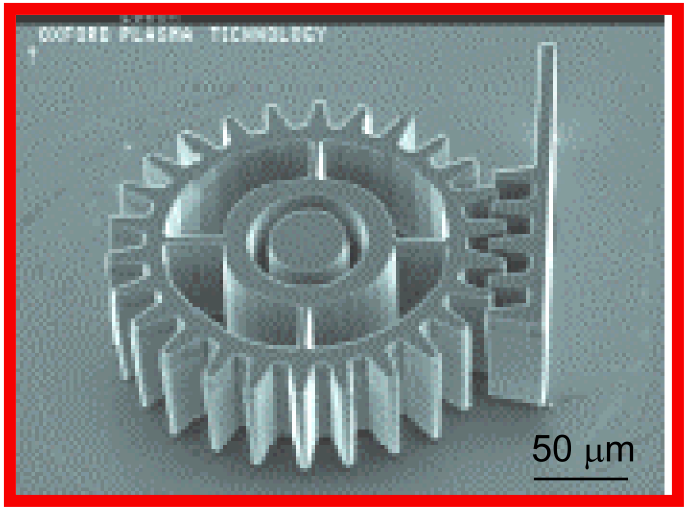
Micromachines or MEMS



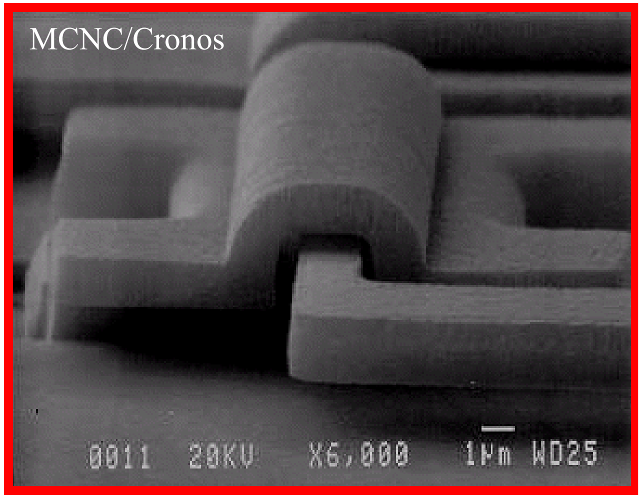
microturbine,



micron-scale moveable mirrors



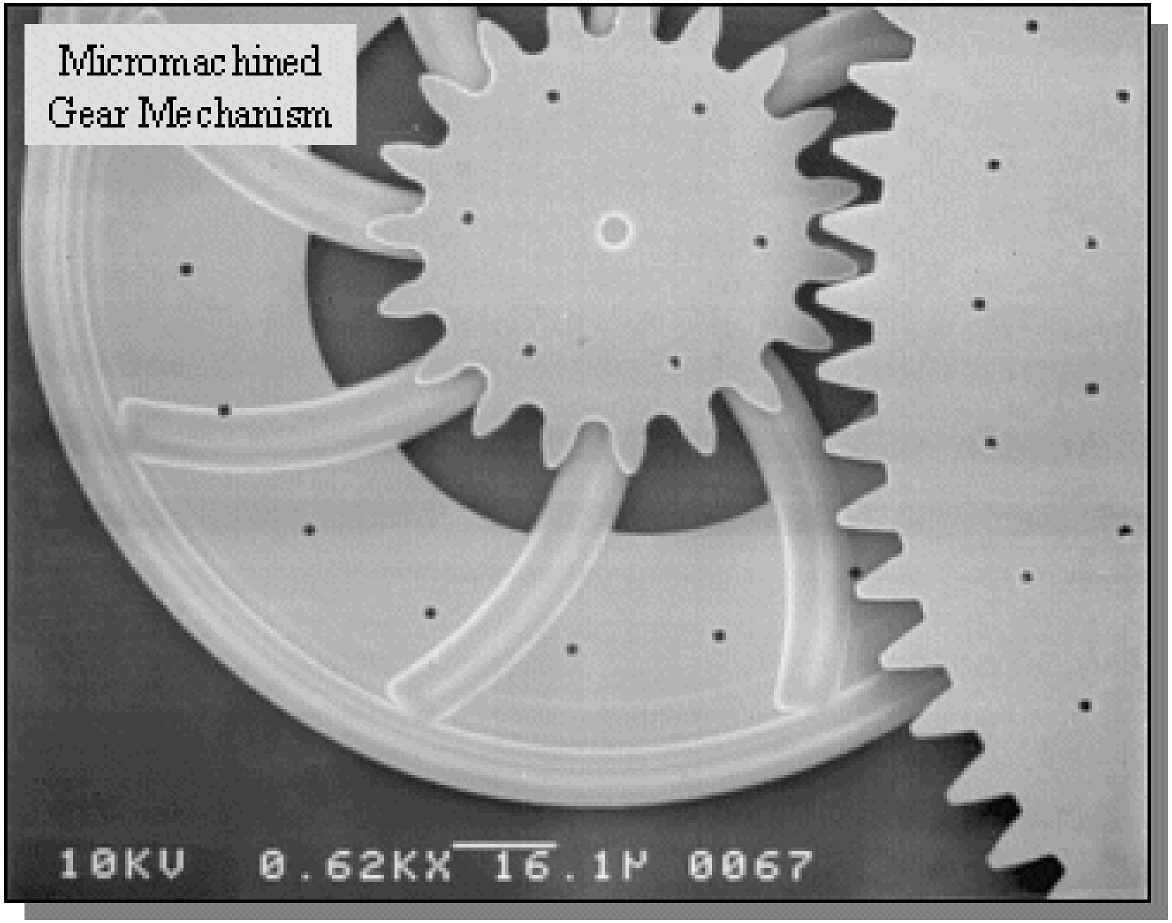
gears



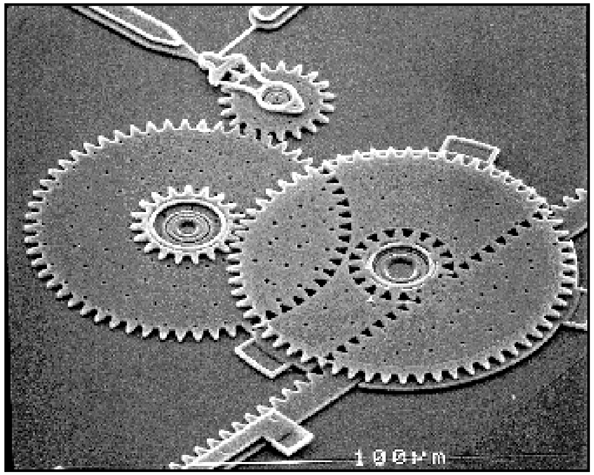
microhinge

Applications: cogs and gears

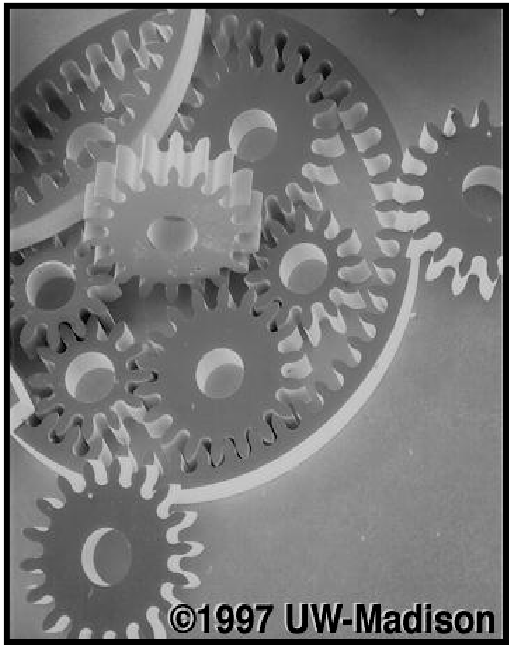
J. H. Comtois, Air Force Research Laboratory, 1998.



Sandia Nat.Labs

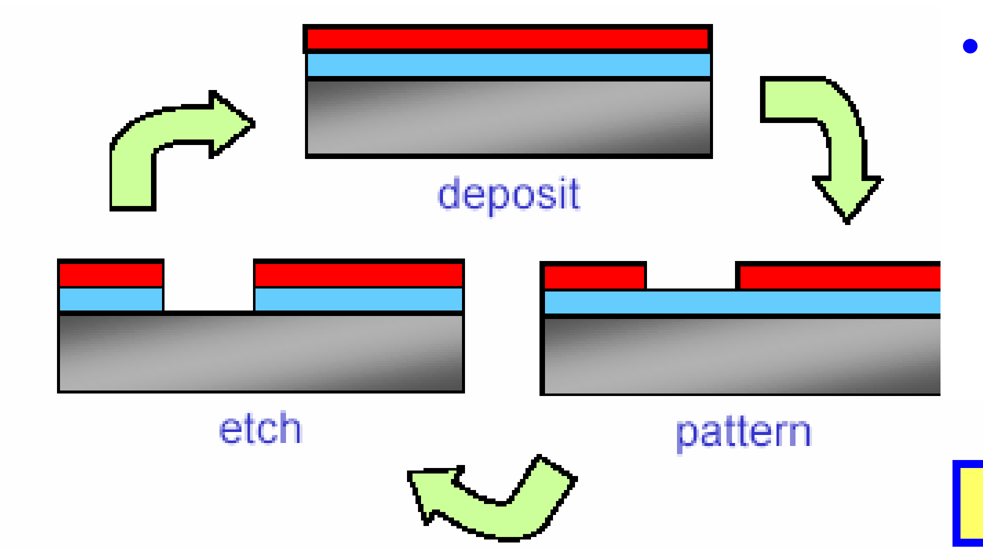


10 μm



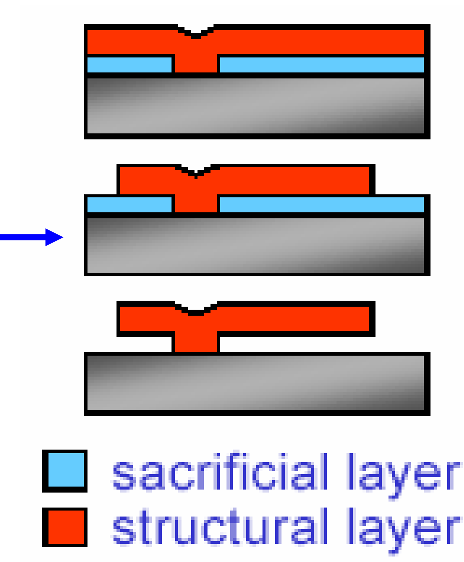
- Micron-scale cogs and gears are used extensively in mechanical micromachines

MEMS Fab: surface micromachining

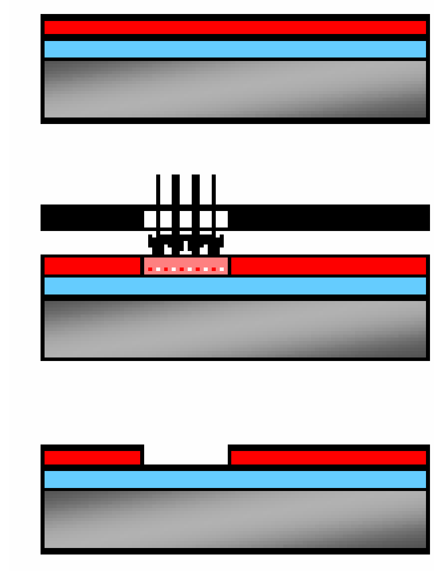


- technique consists of only three major processes:
  - deposition
  - pattern
  - removal

sacrificial etching



- deposition by:
  - oxidation, chemical-vapor deposition, ion implantation
- patterning by:
  - photolithography
- removal by:
  - etching, evaporation

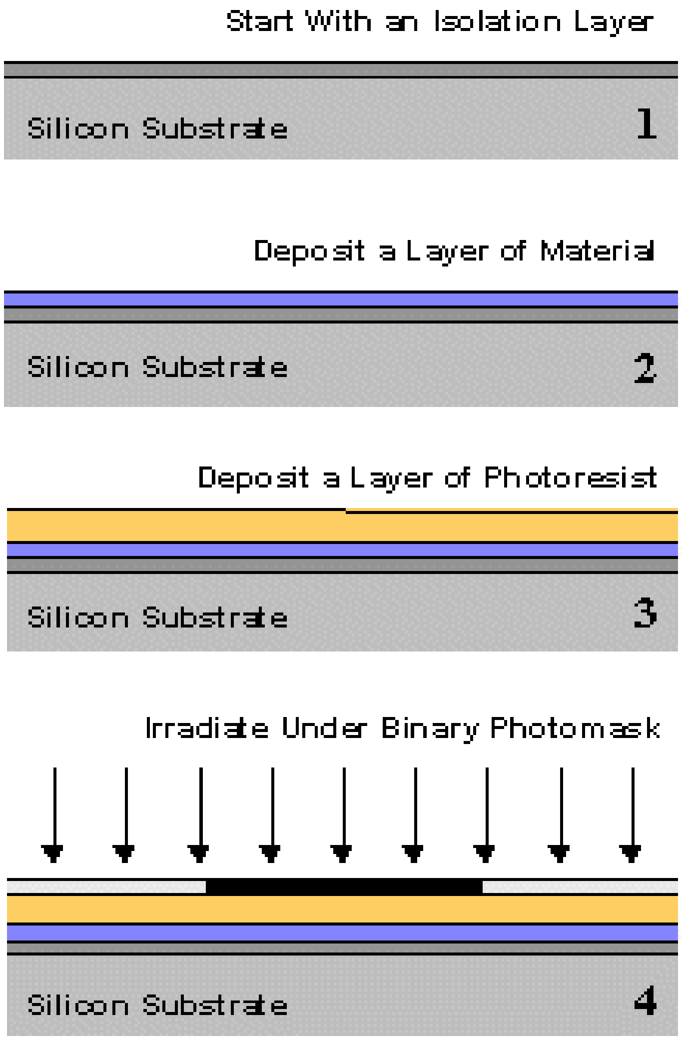


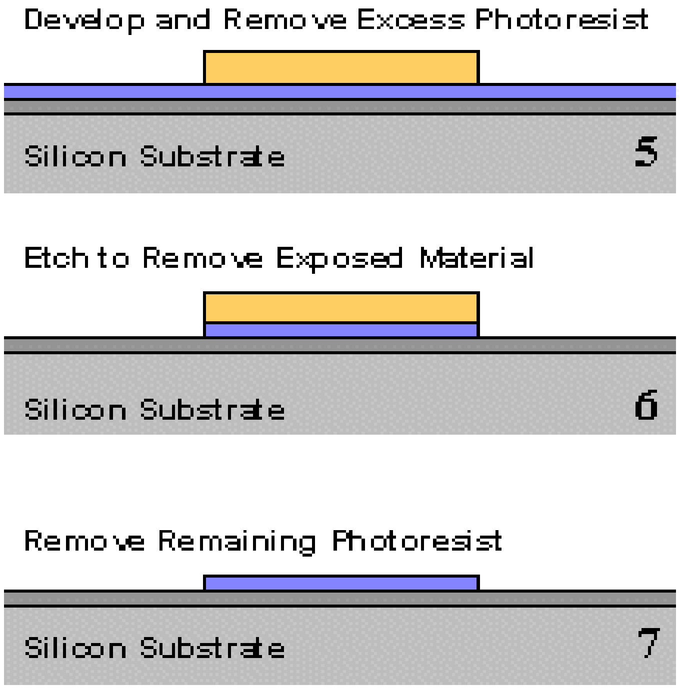
photolithography

- 1-10μm photoresist coating
- optical exposure thru mask
- dissolve exposed resist (developing)

from R. T. Howe and T. Srinivasan (BSAC)

MEMS Fab: surface micromachining



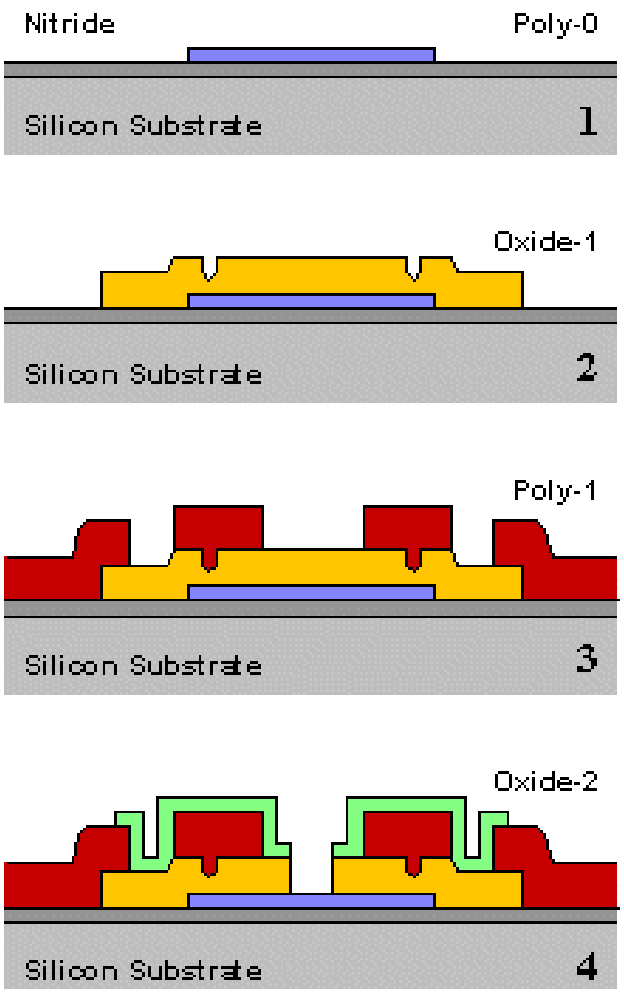


Steps are repeated for each of the structural and sacrificial layers!

Layer thickness, number of layers, and materials depend on the fabrication technology that is used.

from M. A. Michalicek, Un Cooradol

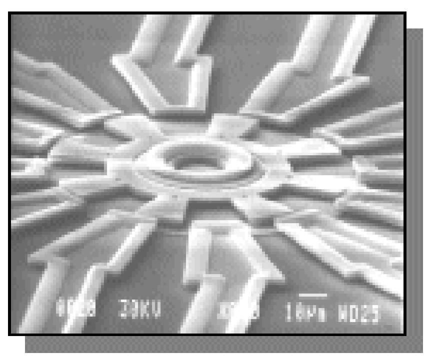
MEMS Fab: micromotor fabrication

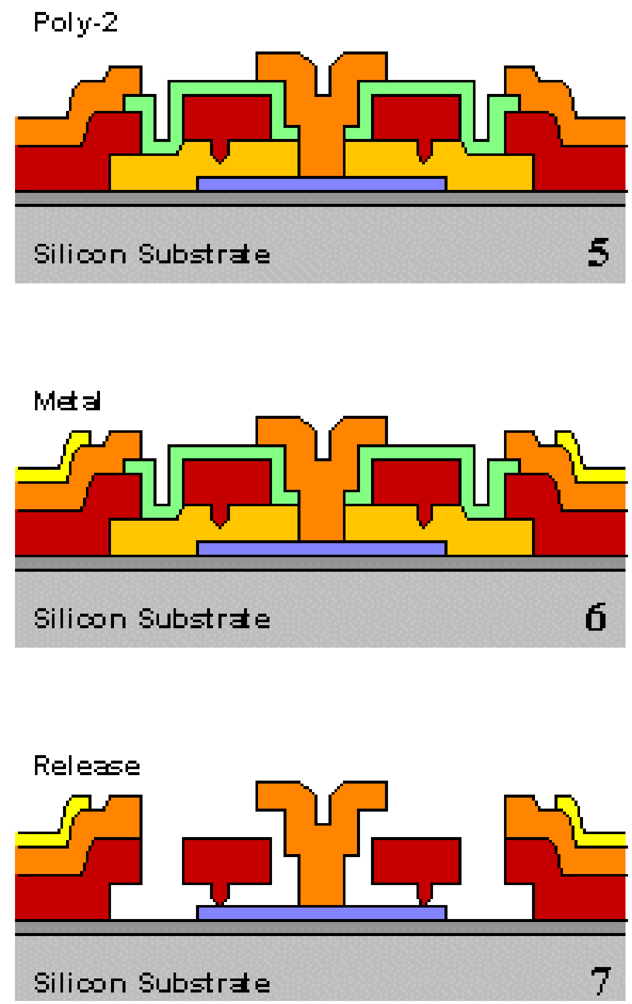


MCNC

After MCNC,
http://www.mcnc.org

Multi-User
MEMS Process
(MUMPS)

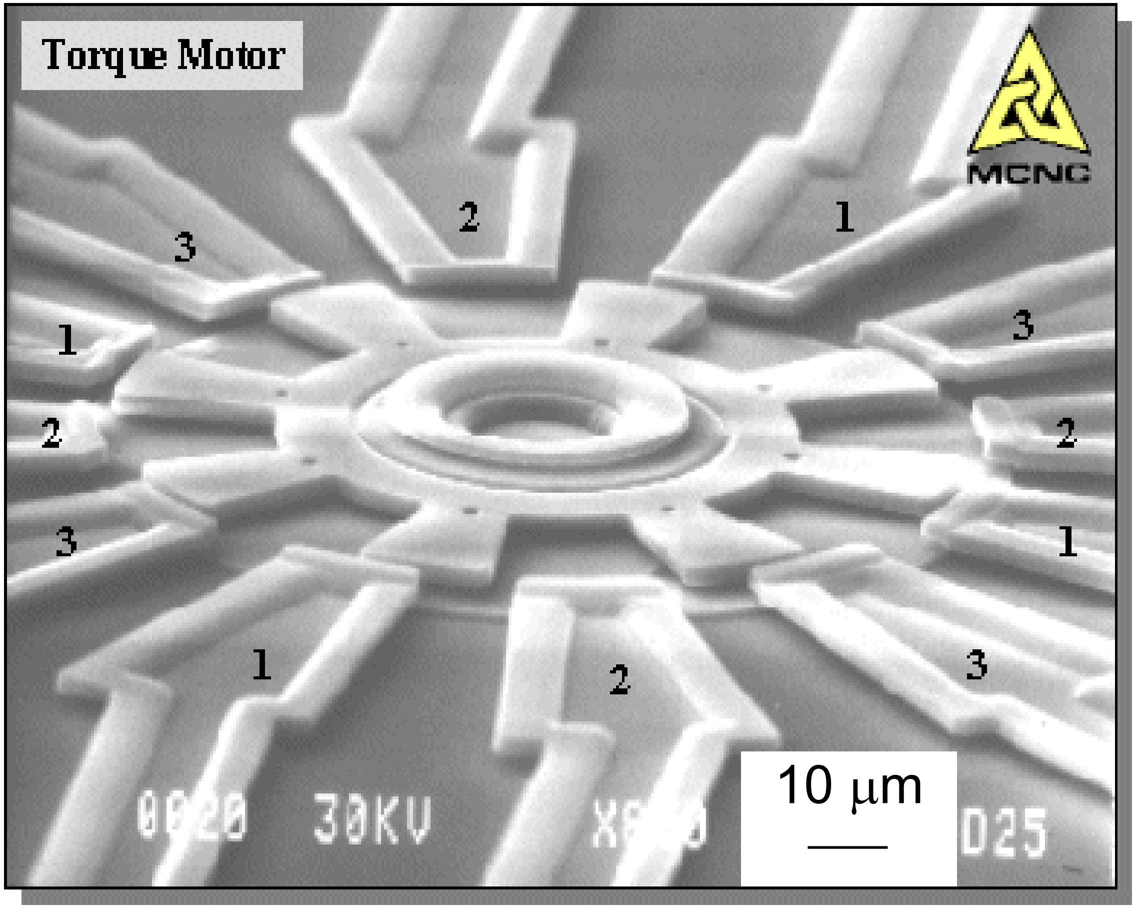


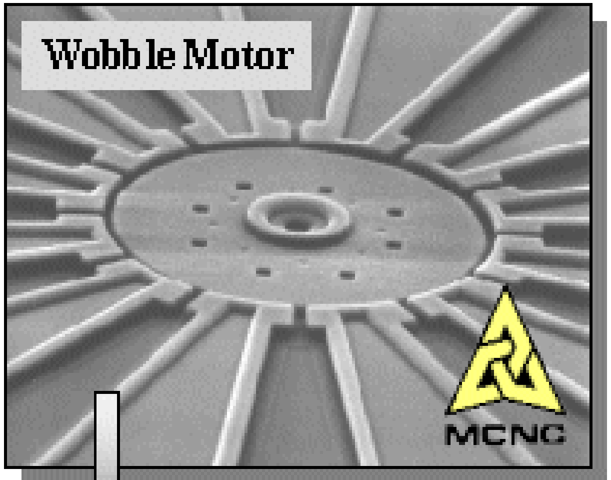


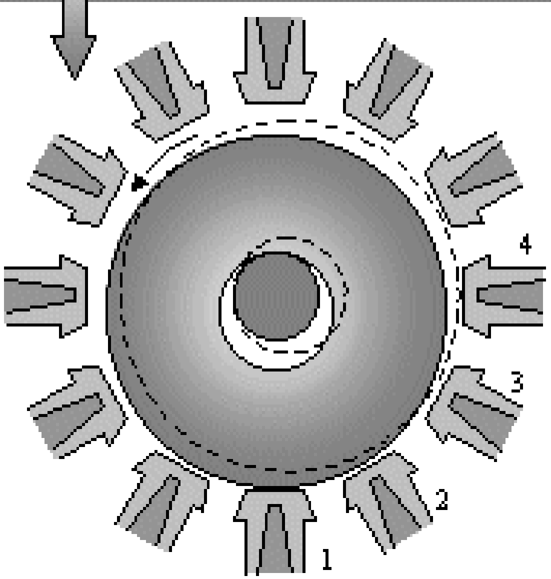
from M. A. Michalicek, Un. Colorado

Applications: wobble motor

Micrographs from MCNC, Http://www.mcnc.org







Electrodes are actuated in sequence to produce rotation:

Torque motor uses four sets of three-phase actuators to excite the rotor.

Wobble motor uses twelve distinct electrodes to lead the play in the rotor bearing.

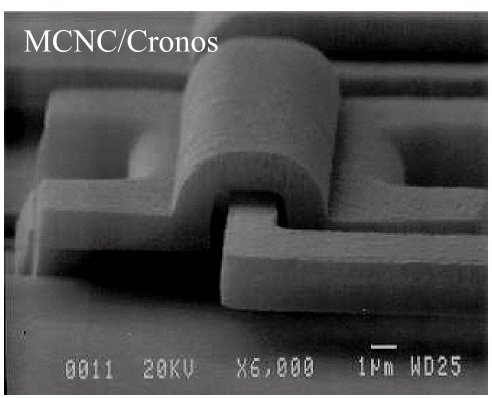
M. A. Michalicek, Un. Colorado

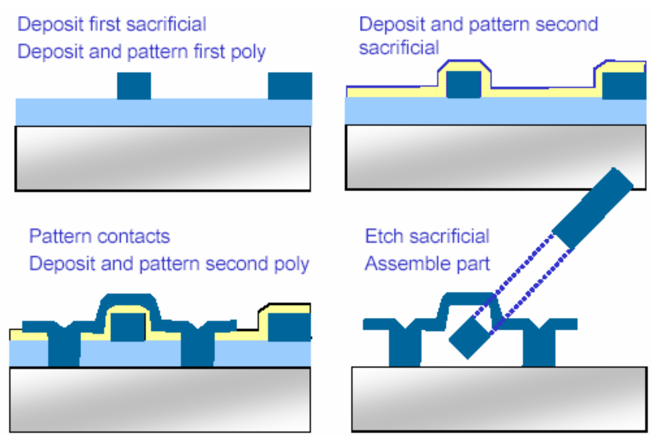
"Pop-Up" MEMS Fabrication

inspired by children's "pop-up" books

closed box assembly

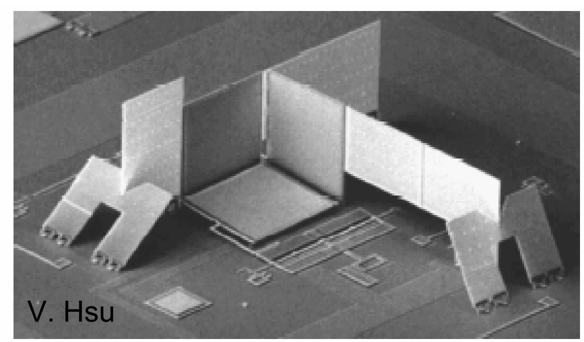
microhinge





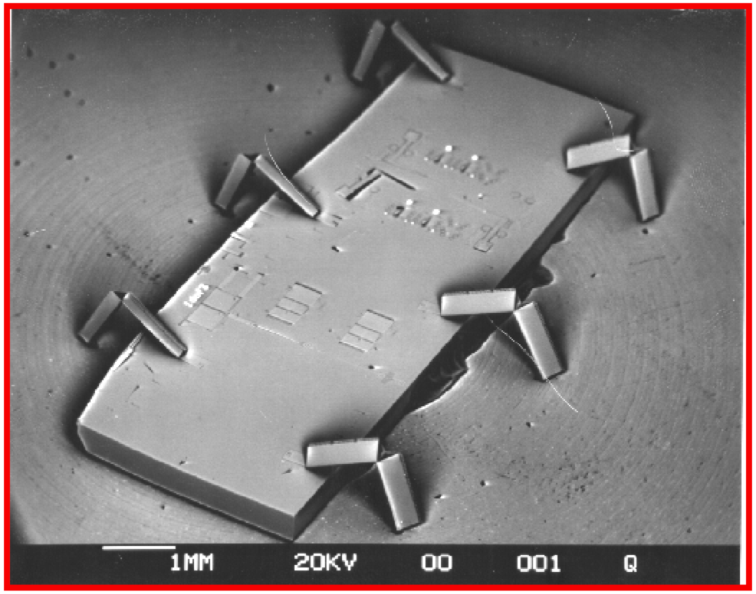
Hinge processing (K.J.S.Pister, BSAC)

corner cube reflector

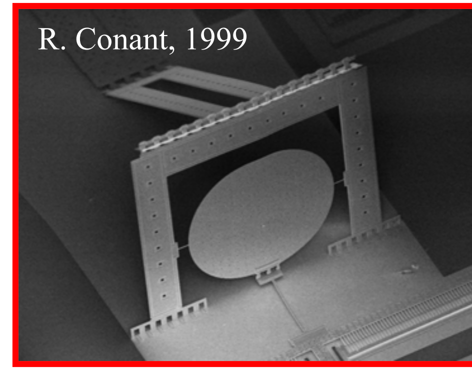


R. T. Howe *et al.*, BSAC

Applications: robots and mirrors

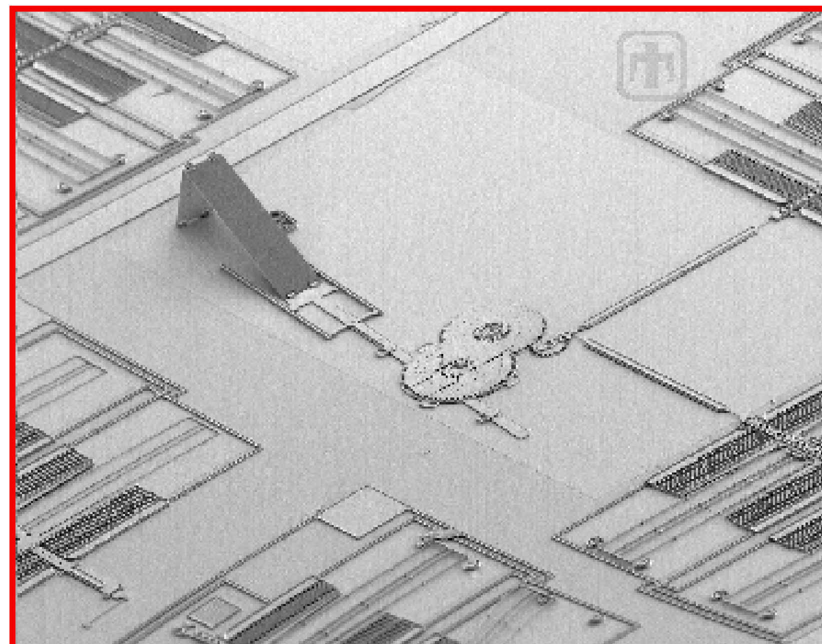


Richard Yeh, BSAC



- Microengine with micro-transmission used to drive a pop-up mirror

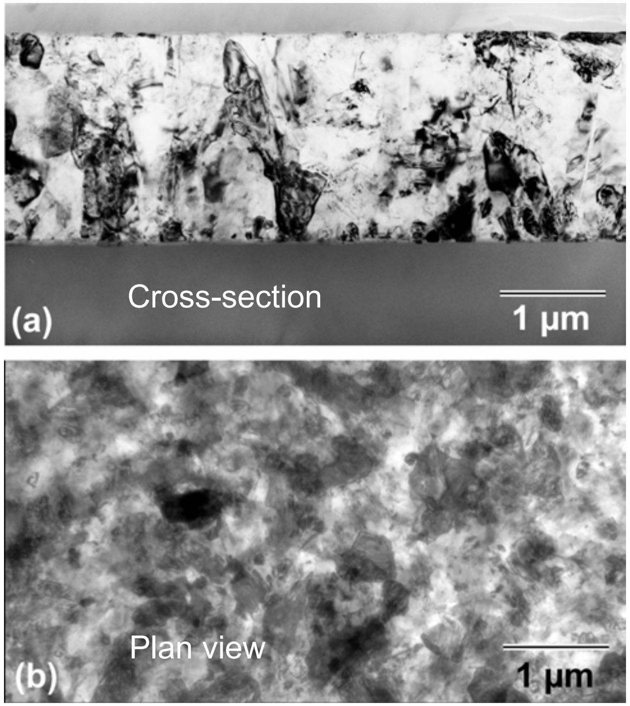
- Millimeter-scale robots, in the form of bugs and flies, use microrobotic components (articulated rigid links, couplings and stepper motors) to control motion



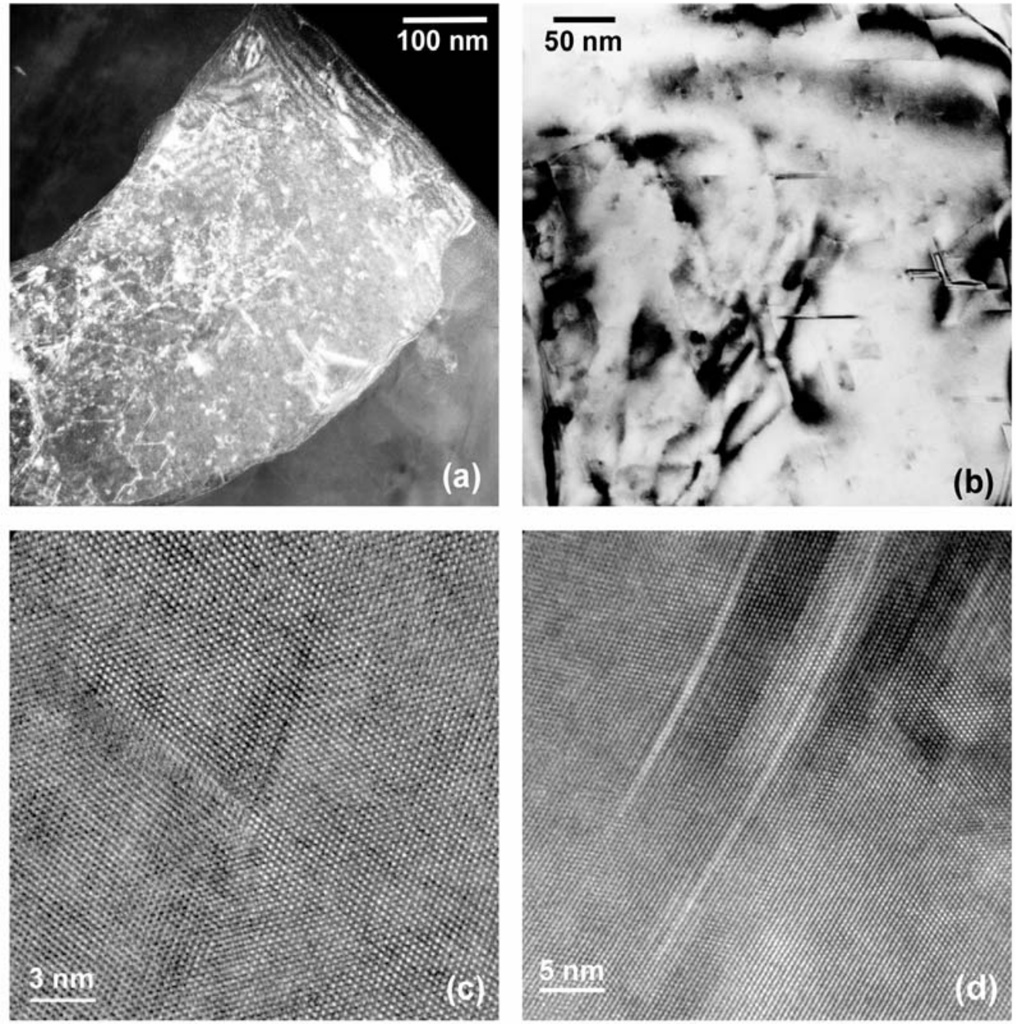
Sandia National Labs

10 μm

Microstructure of Polysilicon Films



1 MeV HVTEM images

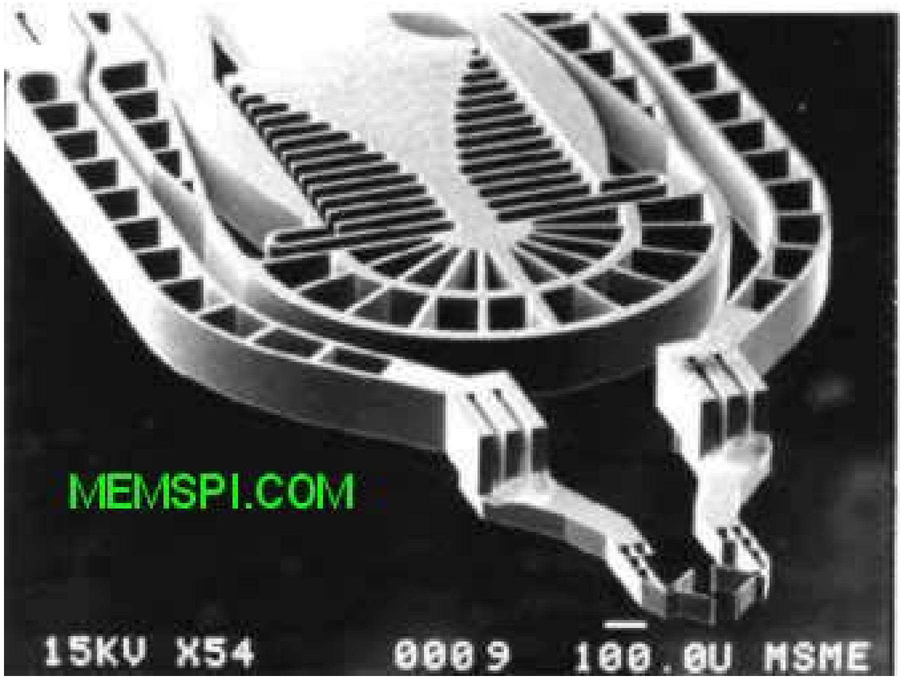


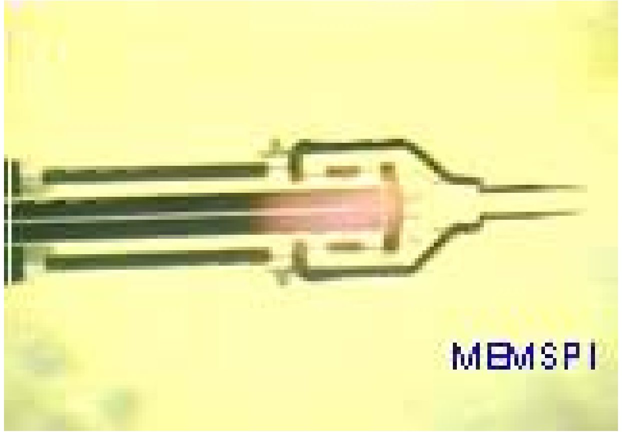
- grain size ~ 100 nm
- twins and defects are present in the atomic structure
- bending strength 3 – 5 GPa

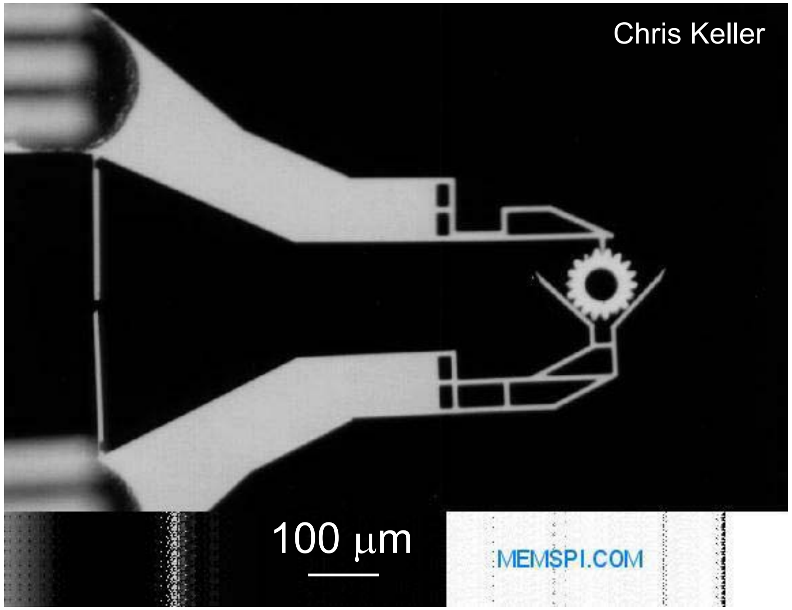
Muhlstein, Stach, Ritchie, *Acta Mater.*, 2002

Applications: microtweezers

Devices are manipulated using microtweezers

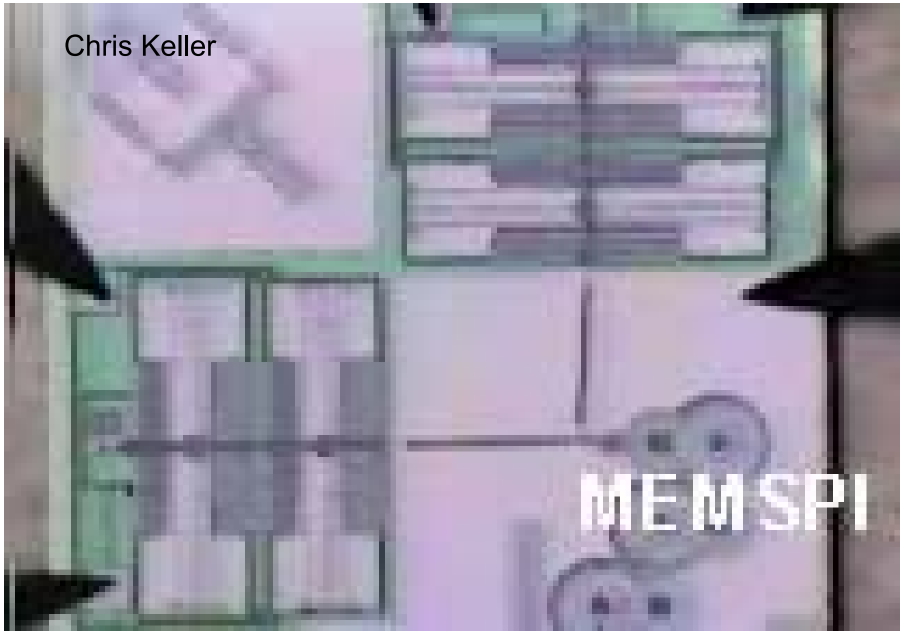






- microtweezer gripping a 100 μm tall nickel gear, provided by Sandia National Laboratories

Applications: micromotors



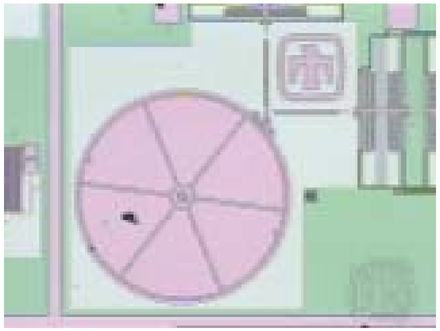
10 μm

- Sandia microenginemoving to rotate gears in a 20,000 to 1 reduction ratio to operate a set of microtweezers

- Rotary stepper motion driven electrostatically

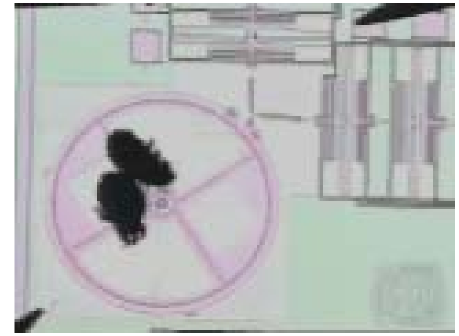
courtesy Sandia National Laboratories, SUMMiT™ Technologies, www.sandia.gov/mstc

Micromotors and Bugs!

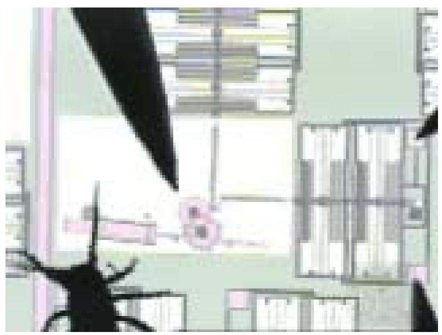


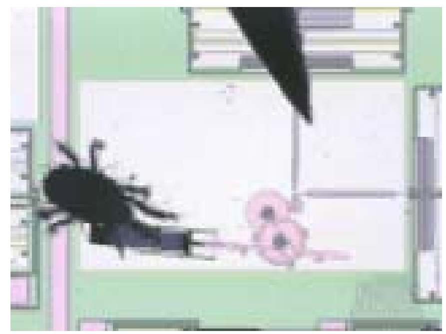
spider mite crossing a gear

two dust mites on a rotor wheel

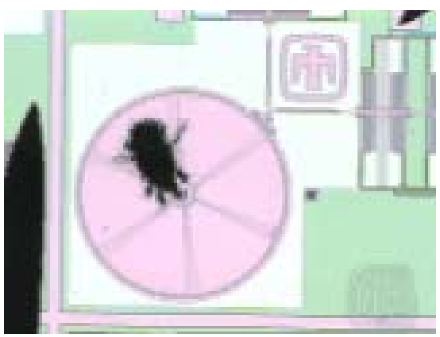


aphid on a micromirror





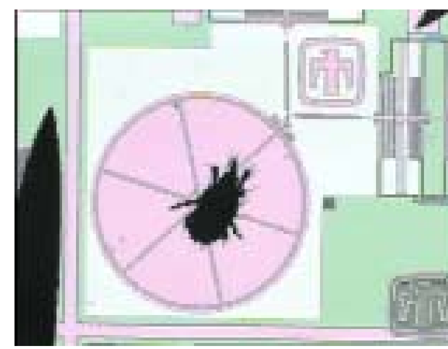
spider mite “tests” a micromirror



spider mite rides a large wheel

10 μm

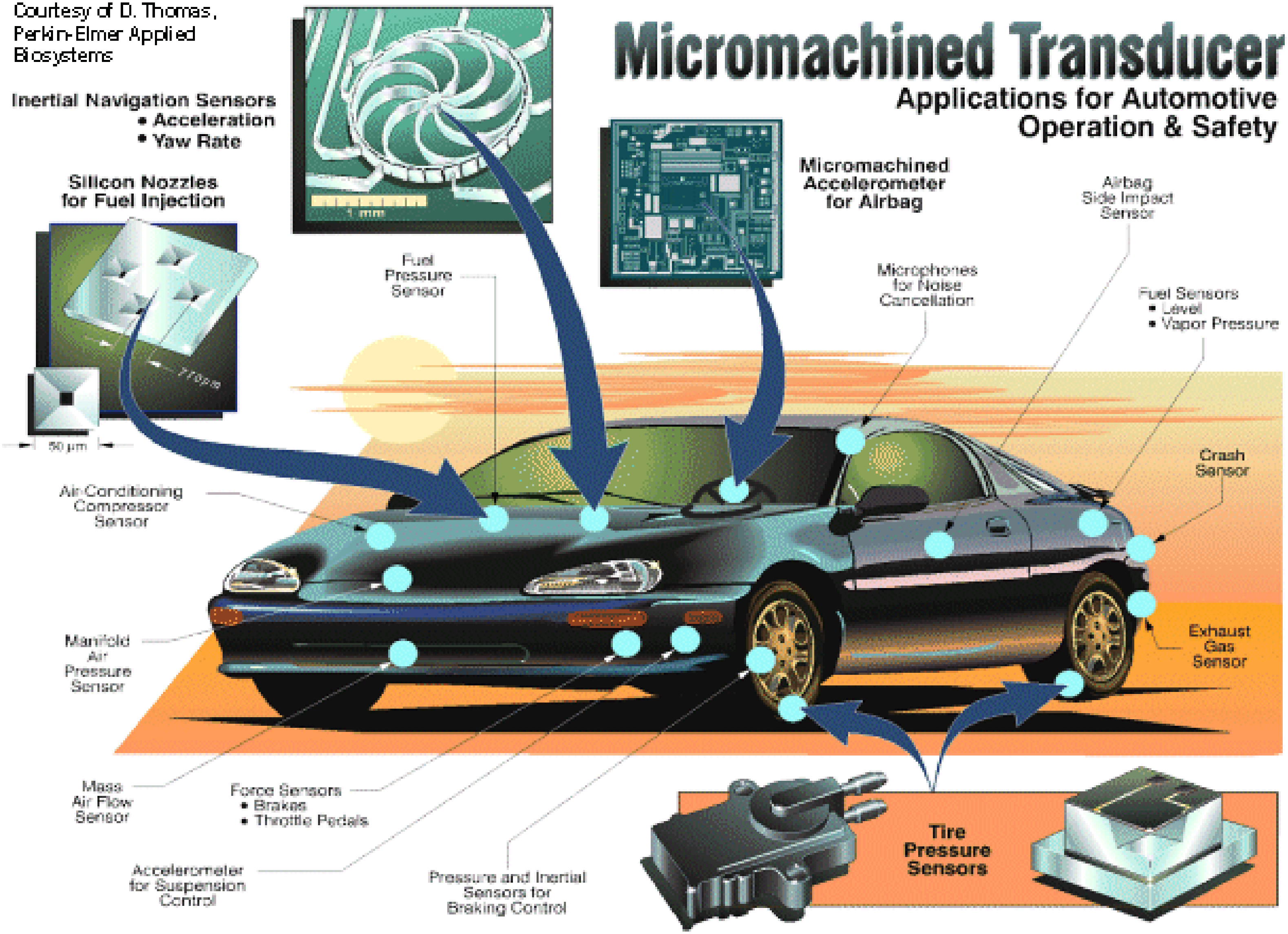
..and it gets a wee bit too fast!



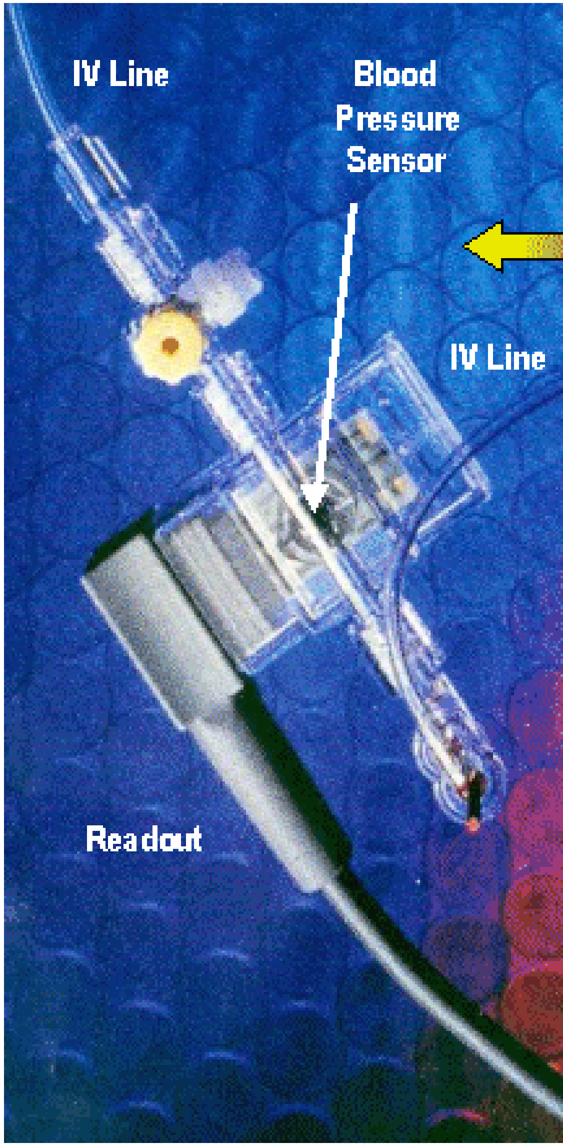
courtesy Sandia National Laboratories, SUMMiT™ Technologies, www.sandia.gov/mstc

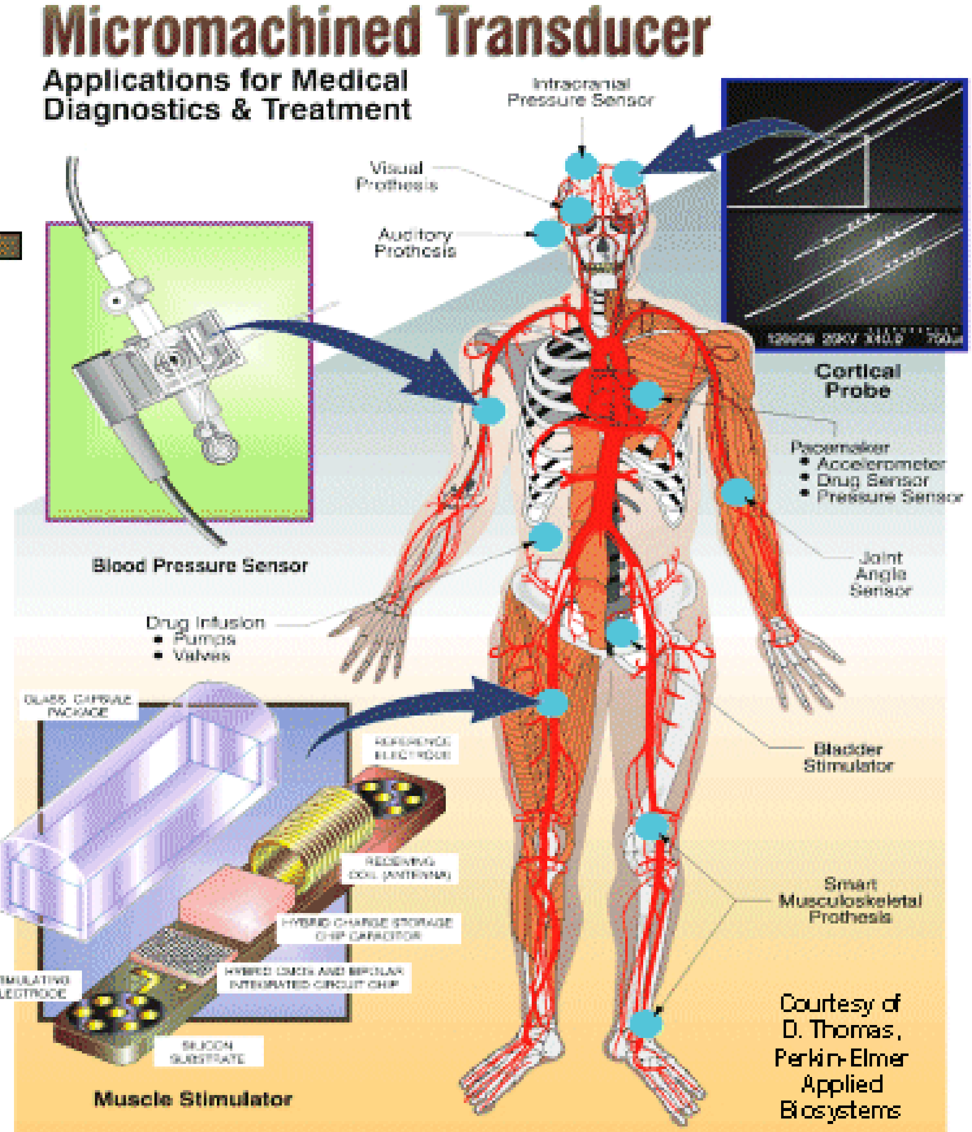
Applications: automotive sensors

Courtesy of D. Thomas, Perkin-Elmer Applied Biosystems



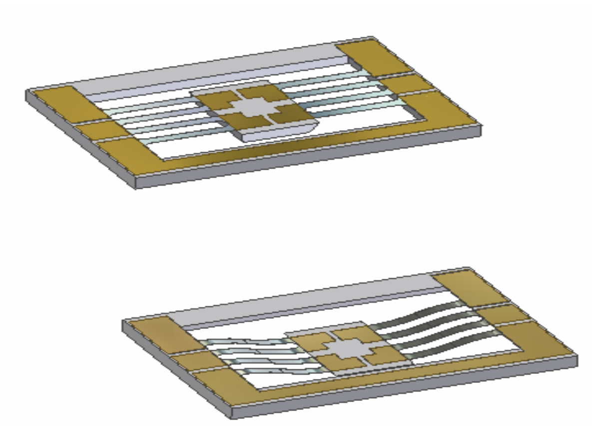
Applications: medical implants

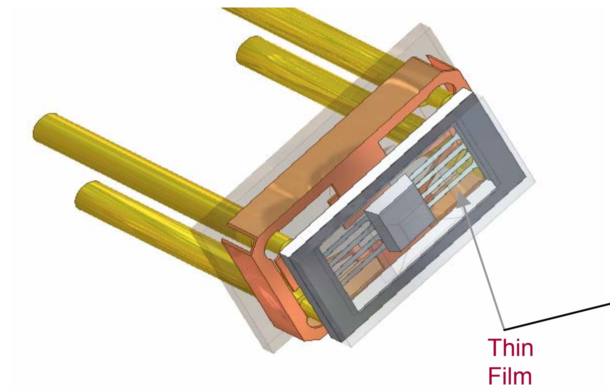


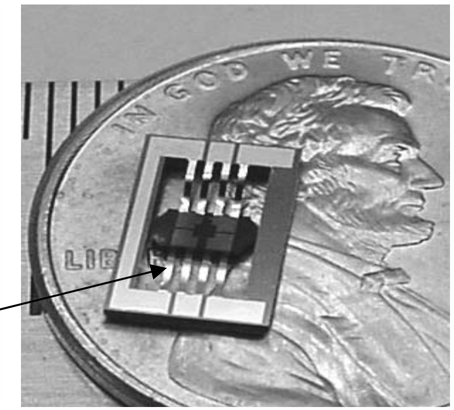


Nitinol thin-films structures

Nitinol thin-film actuators



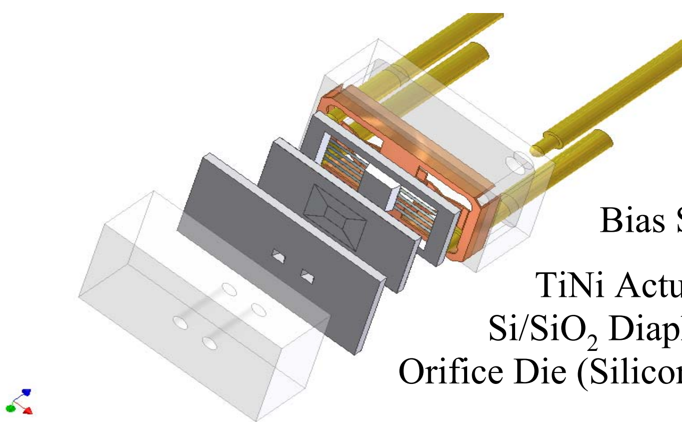




Thin
Film
Nitinol
Ribbons

Nitinol thin-film actuated liquid microvalve

- actuator can deliver a force of 0.5 N
- each gram of Nitinol can deliver 1-6 joules/cycle, far more than the 0.01 joules/cycle for an electrostatic actuator



Spring loaded electrical contacts

Bias Spring (BeCu)

TiNi Actuator Die

Si/SiO_2 Diaphragm Die

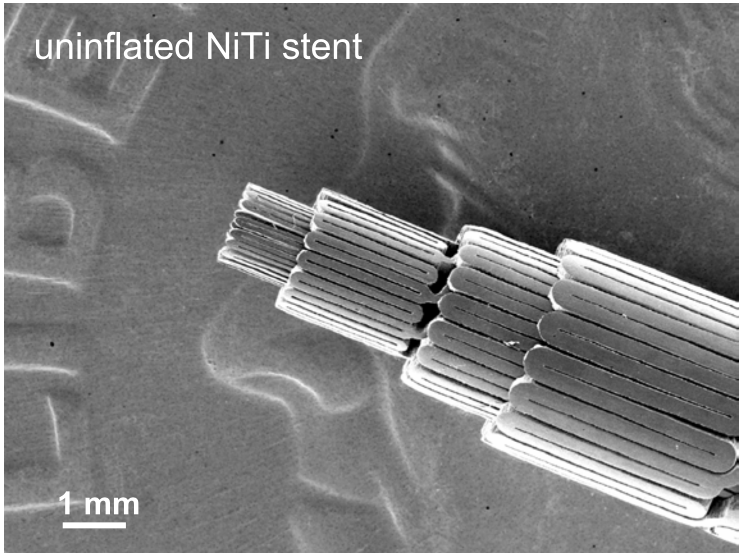
Orifice Die (Silicon)

Manifold (plastic package)

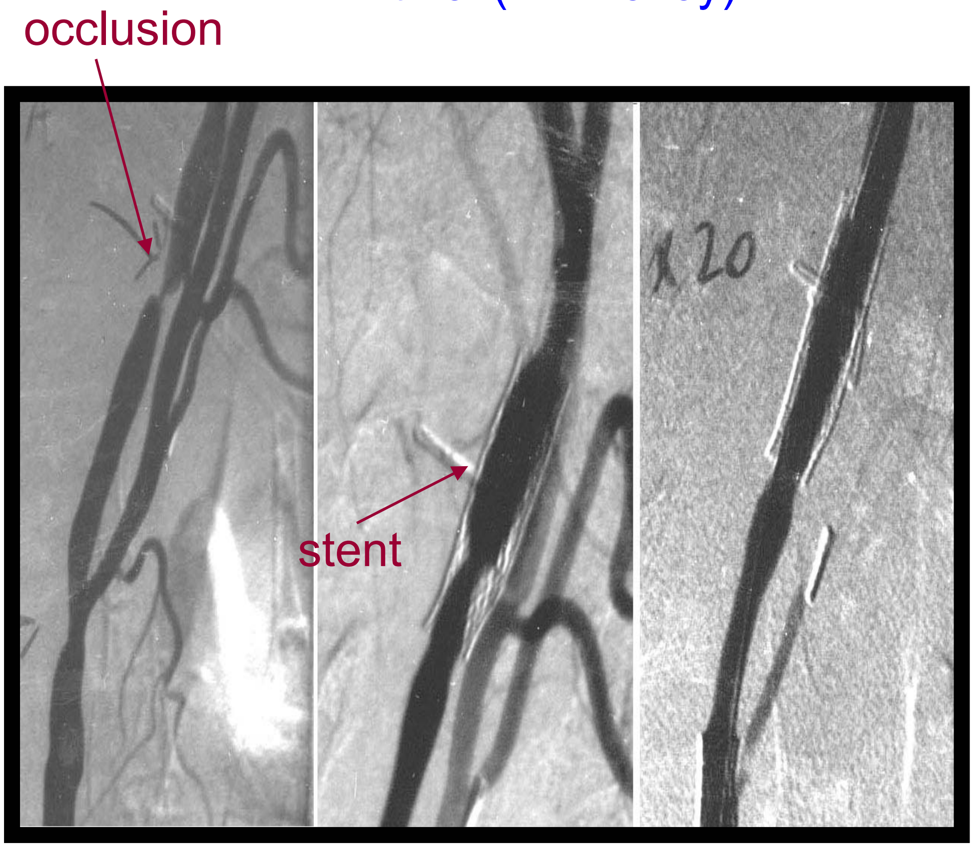
Nitinol is a 50:50 Ni-Ti alloy with shape-memory and superelastic characteristics

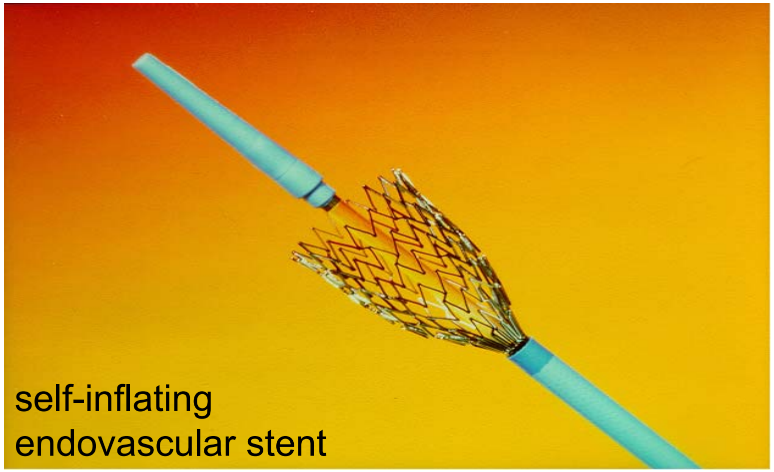
made by the TiNi Alloy Company, San Leandro, CA

Stenting of Arteries



- Stents manufactured with:
  - stainless steel
  - cobalt-chronium alloy
  - Nitinol (Ni-Ti alloy)

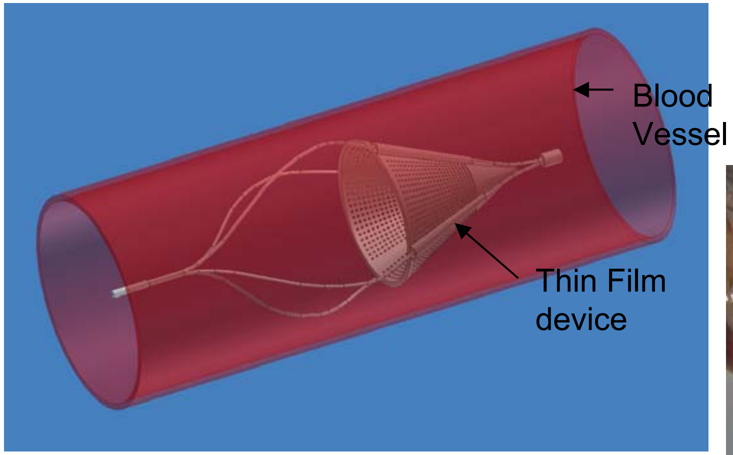




made by NDC, a J&J Company, Fremont, CA

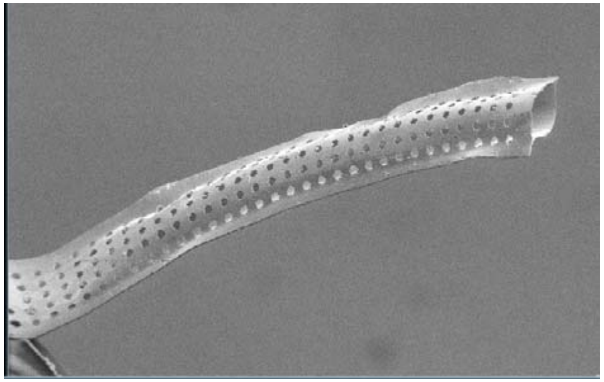
Nitinol thin-films structures

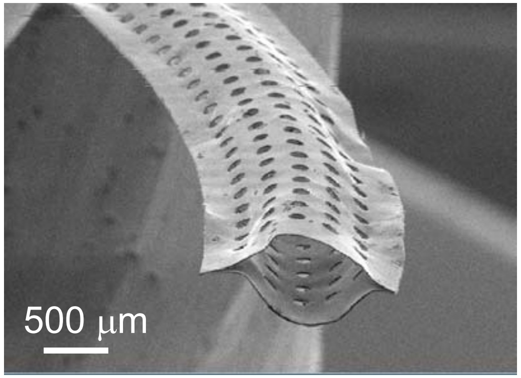
Intravascular blood clot retriever device



- “microfabed” from 5 μm thick thin film Nitinol

Stents for the human eye



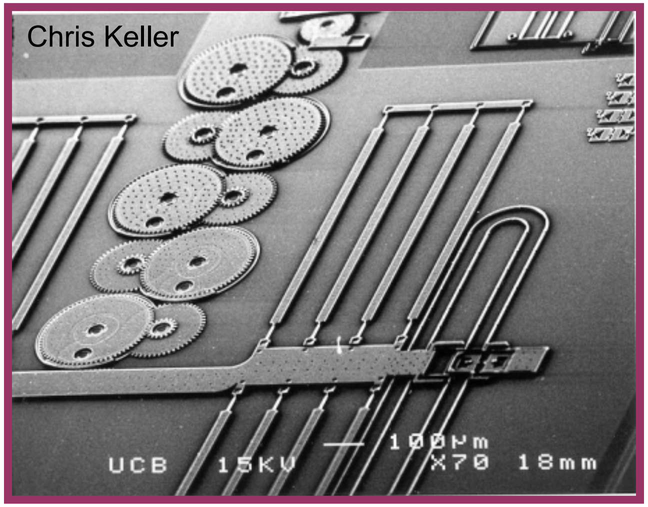


- tiny thin-film stents that are implanted into the Schlen’s canals that drain fluid around the iris of the eye

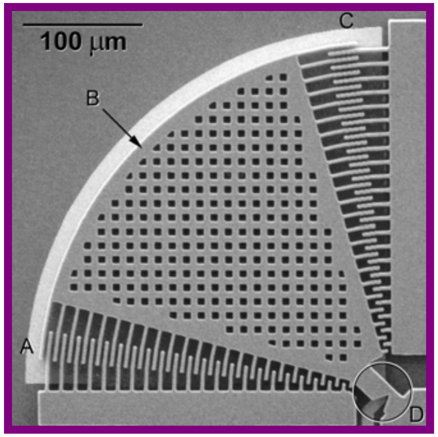
made by the TiNi Alloy Company, San Leandro, CA

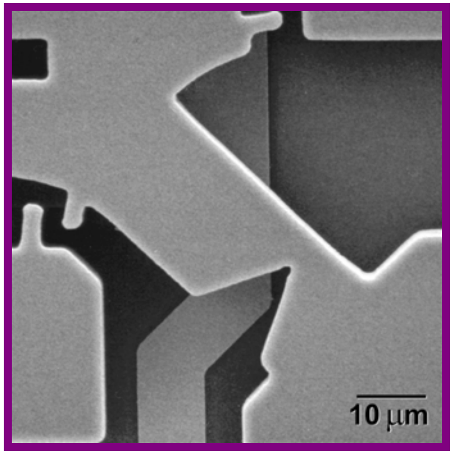
Mechanical Testing at the Micro/Nano Scale

- assessing the mechanical properties of materials and components at the micro- and nano-scales is of critical importance for device reliability and durability
- current technologies are essentially at the micro-scale, although research shrinking these techniques to smaller dimensions



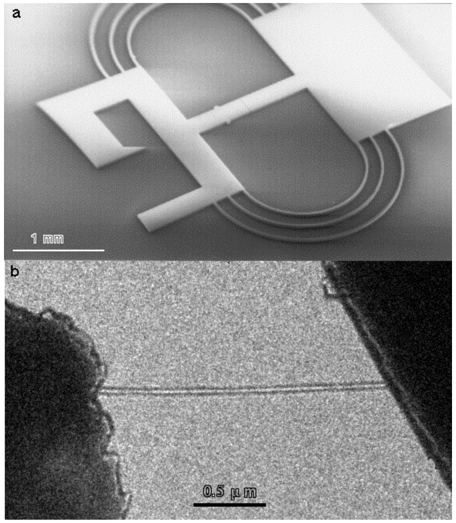
electrostatically-driven mechanical testing system designed to operate *in situ* in the TEM



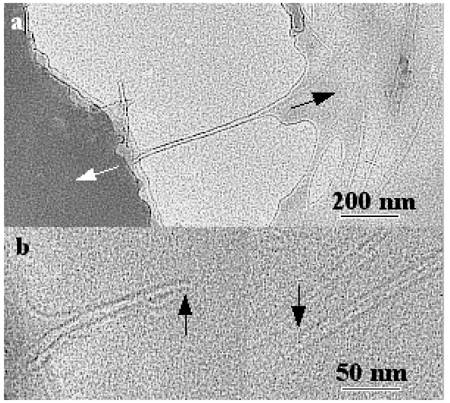


on-chip resonant fatigue device used to evaluate the high-cycle fatigue endurance of 2-µm thick silicon films

Brown, Van Arsdell, Muhlstein, *et al*.



Denchzk, Ritchie, Zettl, *et al*.

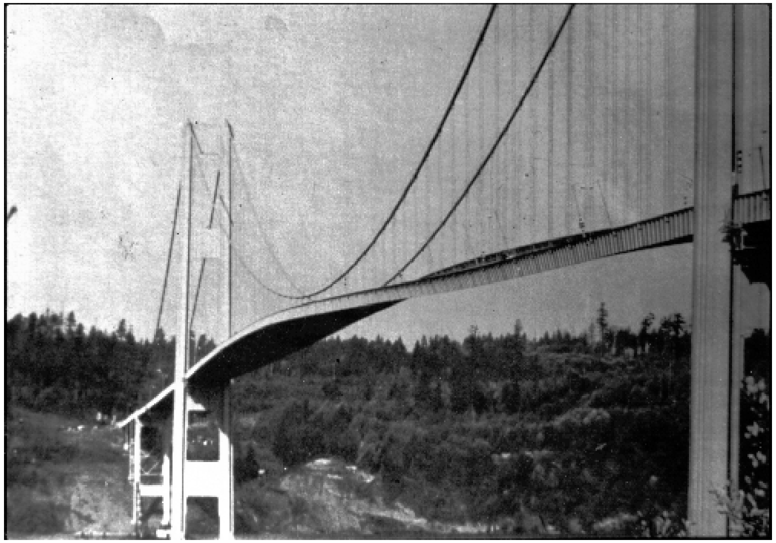


in situ mechanical test in the TEM to measure the strength of a 12-nm thick carbon nanotube

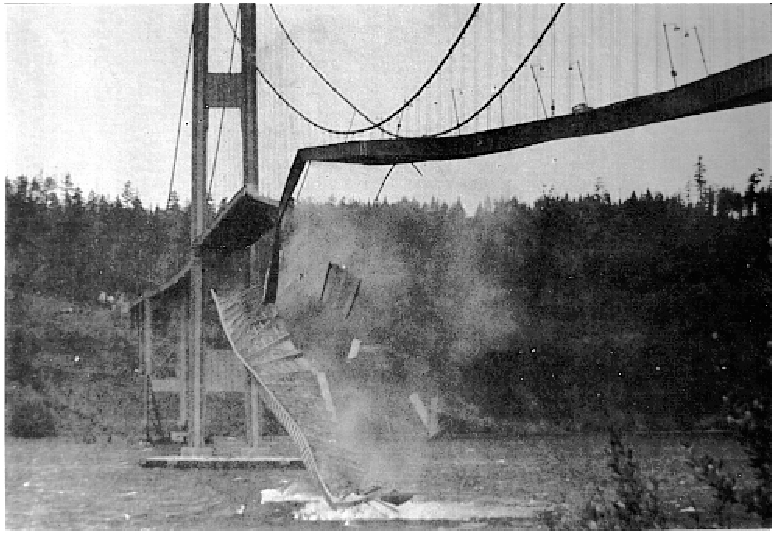
How do things break?

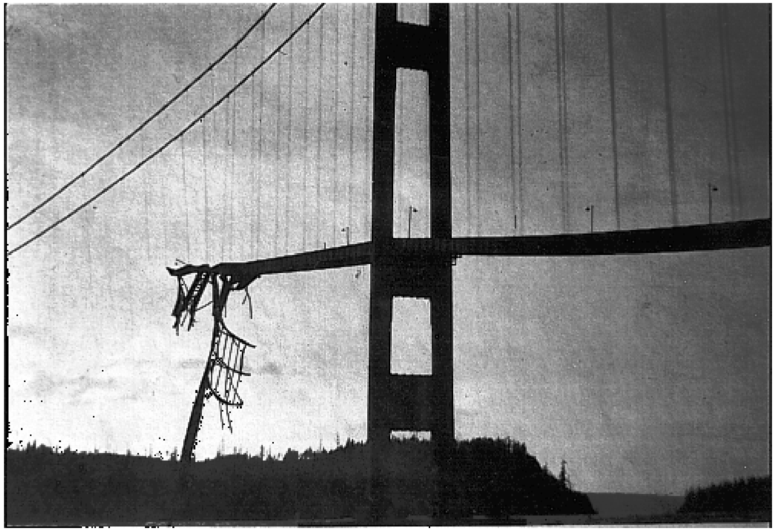
- by plastic deformation - yielding
  - e.g., by bending a paper clip
- by (instantaneous) fracture
  - e.g., by breaking a pencil or a tooth or by impact fracture
- by fatigue (delayed fracture)
  - e.g., by bending that paper clip back and forth several times
- by environmentally-assisted cracking (delayed fracture)
  - e.g., by bending that paper clip back and forth under (salt) water
- by wear (surface damage)
  - e.g., by simply wearing something out

Failure by Plastic Deformation



- plastic (permanent) deformation of a bridge
- deformation led to eventual collapse
- Tacoma Narrows suspension bridge, near Puget Sound, failed on at 11 am Nov. 7, 1940, after only having been open for traffic a few months

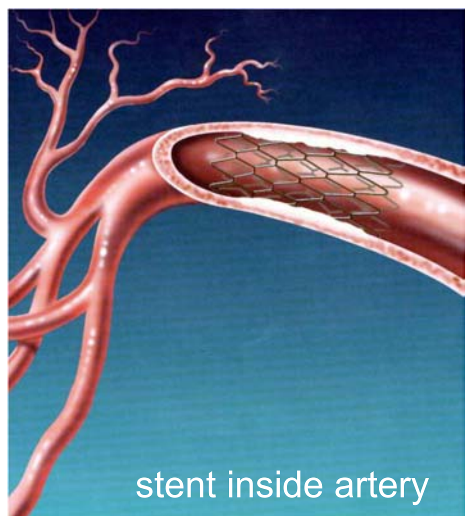


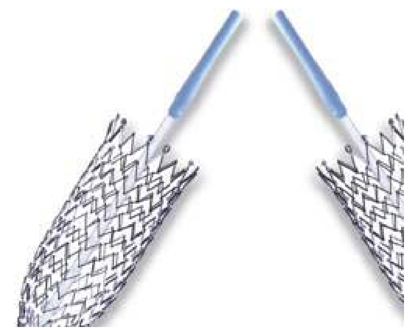


Failure by Plastic Deformation

- most materials only deform reversibly (i.e., elastically) when deformed a small amount (e.g., when stretched for less than 1% change in length)
- after that the deformation is permanent (plastic deformation)
- however, a very few metals, so-called shape-memory/superelastic metals, e.g., Nitinol, are much more flexible

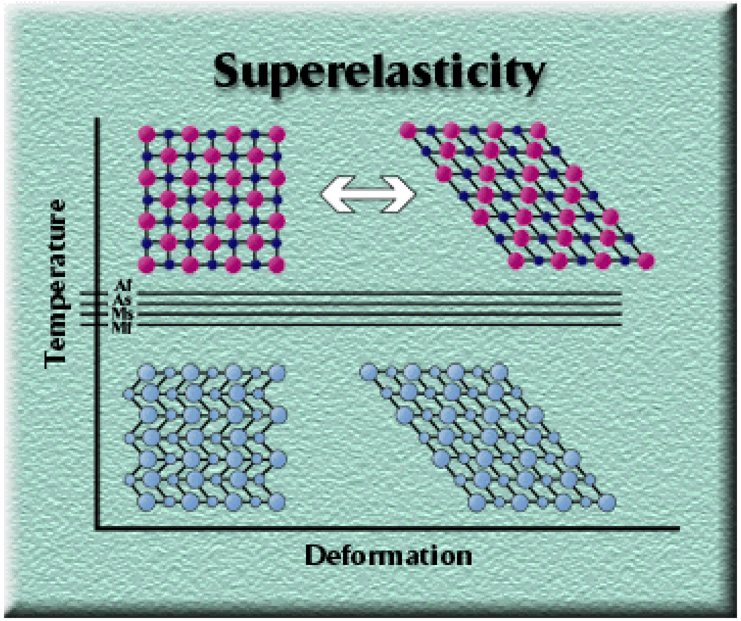
Nitinol is a 50:50 nickel-titanium alloy



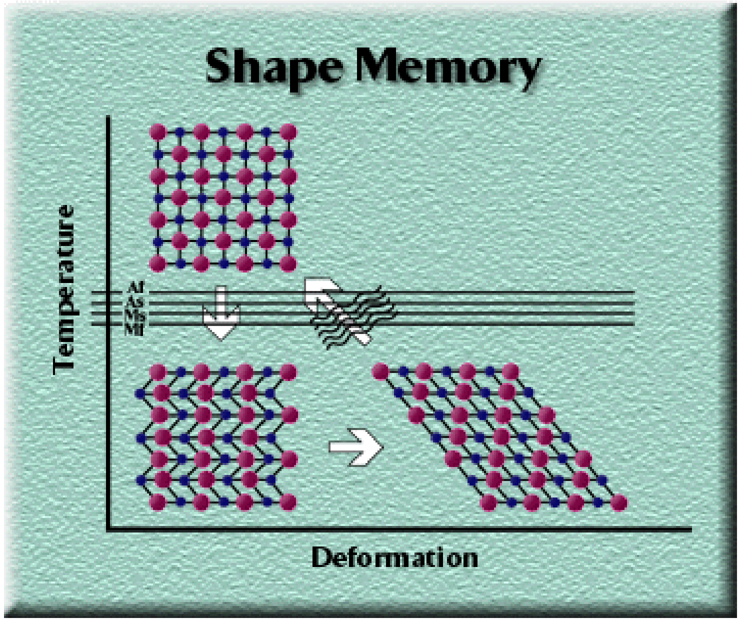


Nitinol is used for eye-glass frames, dental drills and endovascular stents

Superelastic/Shape-Memory Alloys



- **Superelasticty** is the property of a material to display very large elastic (reversible) deformation
- most metals show 1% elastic elongation; superelastic metals, such as Nitinol and Cu-Al-Ni can show ~8 to 15%



- **Shape memory** is the property of a metal that is deformed at a lower temperature to return to its original shape when the temperature is raised again
- both phenomena result from a reversible change in atomic structure of the metal, on heating/cooling or deformation

after NDC, a J&J Company, Fremont, CA, at http://www.nitinol.com

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  - e.g., by simply wearing something out

Instantaneous Impact Fracture

Brittle fracture of SS Schenectady, Jan. 1943

- 500 T2 tankers and 2700 Liberty ships were built during WWII
- prefabricated all-welded construction, with brittle steel
- one vessel was built in 5 days!

- initially, some 30% of Liberty ships suffered catastrophic failure
- cracks started at stress concentrations (e.g., hatchways) and propagated rapidly through the steel hull as the metal became too brittle at low temperatures

SS John P. Gaines split in two in 1943

Instantaneous Impact Fracture

- Air France charter flight from Paris to New York - July 25, 2000
- the Concorde crashed into a hotel shortly after take-off, 5 miles from airport, with 109 fatalities
- attributed to a piece of metal on the runway causing the bursting of a tire
- the impact of the tire debris on the fuel tank punctured it, leading to loss of engine power, and the subsequent crack
- an example of *foreign-object damage (FOD)*

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Fatigue & Delayed Fracture

- De Havilland Comet, first commercial jet aircraft, had five major crashes in 1952 - 54 period
- caused by fatigue cracks initiated at square windows, driven by cabin pressurization and depressurization

- Aloha Airlines Boeing 737, in route from Hilo to Honolulu (April 1998) undergoes explosive decompression – 1 fatality
- caused by a weakening of the fuselage due to corrosion and small cracks – led to Aging Aircraft Initiative

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  - e.g., by bending that paper clip back and forth under (salt) water
- **by wear (surface damage)**
  - e.g., by simply wearing something out

Failure due to Wear

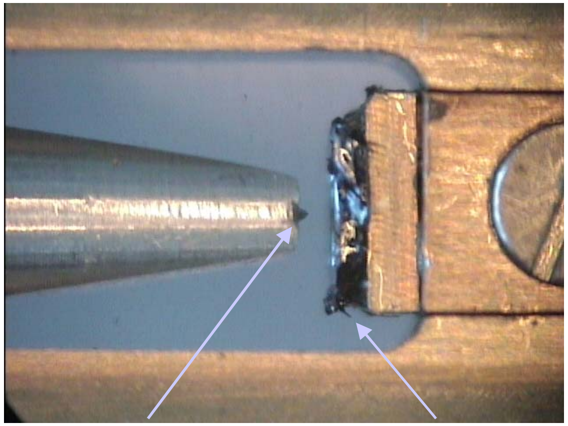
- A major wear problem is with railroad tracks, where surface wear from metal-to-metal rolling contact can damage the rails leading to derailment

Rail collapse leads to derailment of a locomotive in Driffield, UK, in 1981

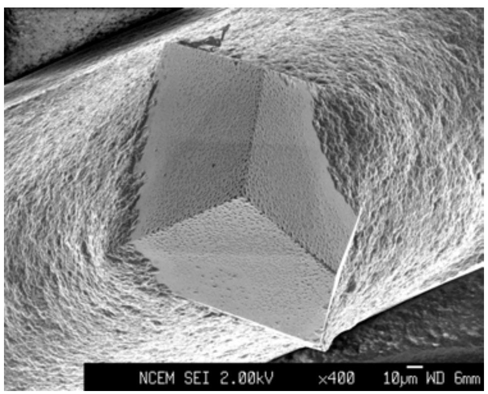
Derailment of 100 ton tank wagon and the rest of the train in Lincolnshire, UK in 1982

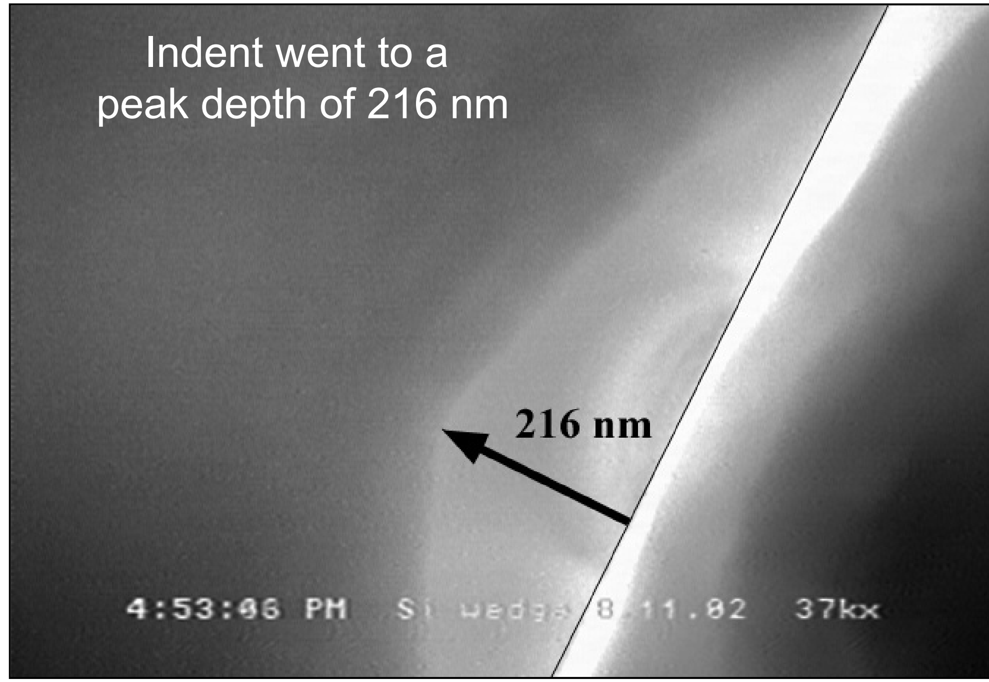
from http://danager-ahead.railf.net

Nano-indentation Methods

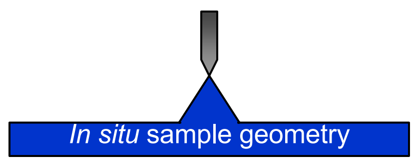


diamond sample

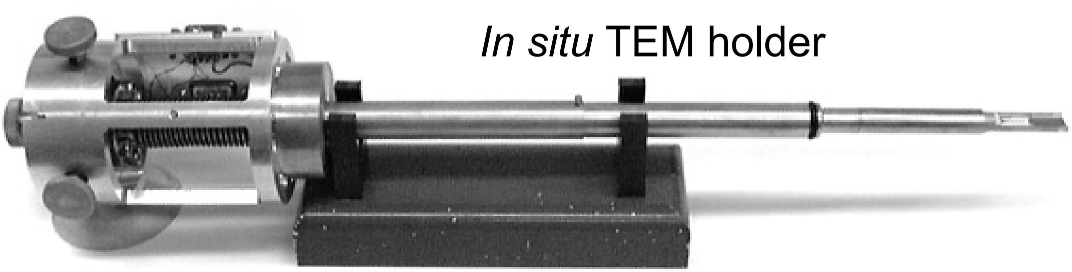




indenter



In situ TEM holder

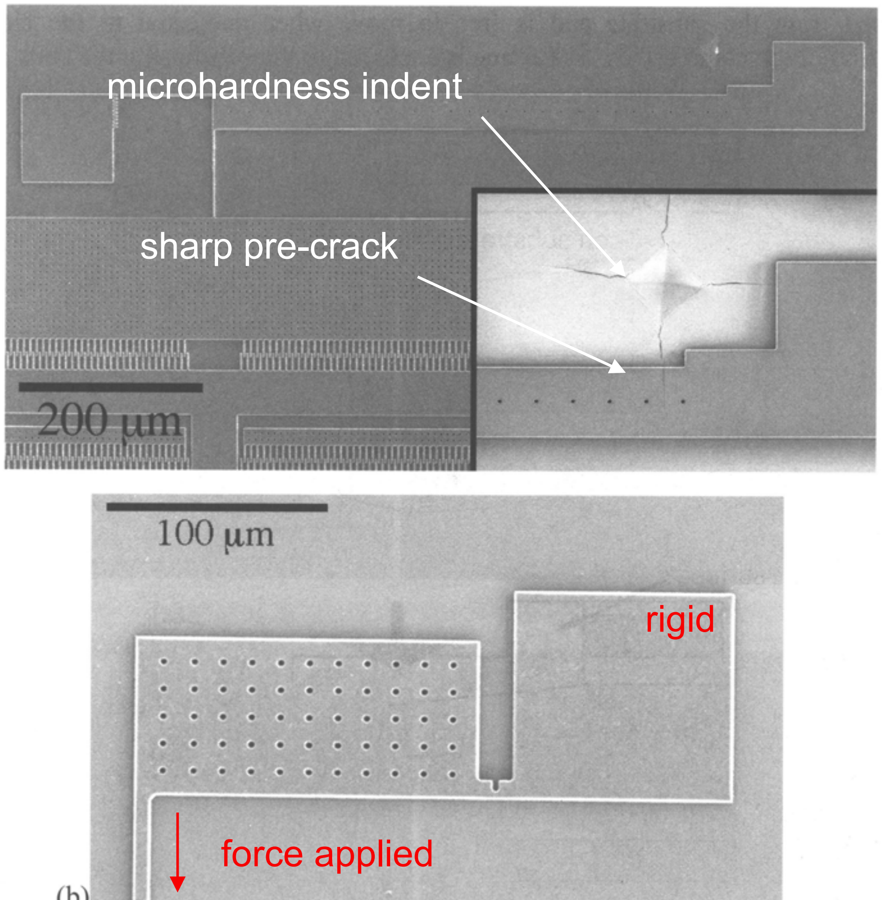


- indentor is mechanically driven into the surface of a material
- the response of the material is measured (stress v. strain)
- the deformation is imaged

Wall & Dahmen, 1997

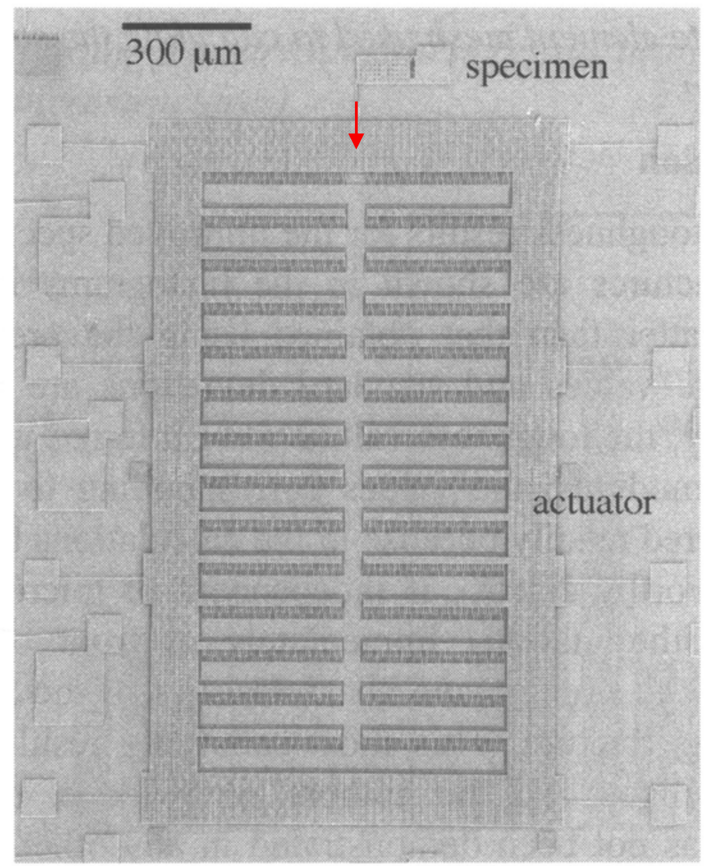
Minor, Stach, *et al*., Phys. Rev. Lett.., 2003

Measurement of Fracture Resistance



(a)
(b)

- *a cantilever is partially cracked and then broken in bending*

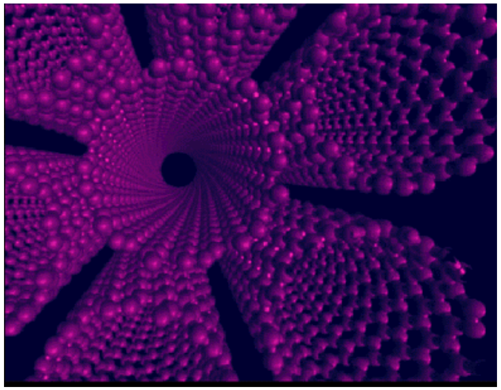


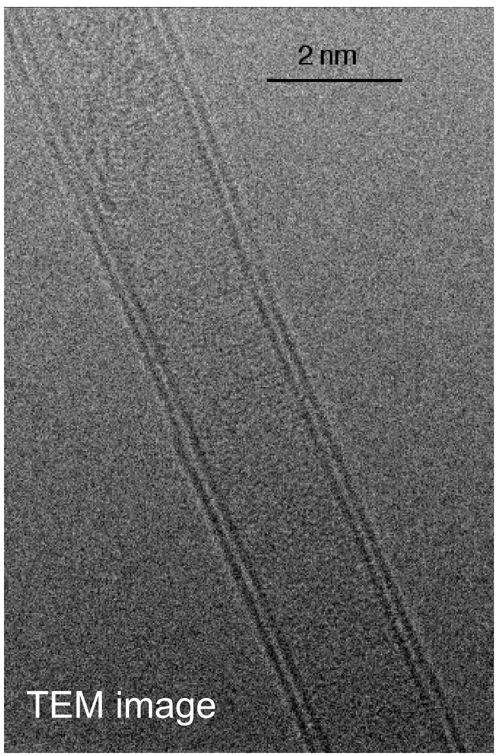
- measurement of the fracture resistance, i.e., the fracture toughness, of thin-film silicon using MEMS

Ballarini *et al.*, ASTM STP 1413, 2001

Mechanical Testing of Carbon Nanotubes

- Carbon nanotubes, few nm in diameter, claimed to be the world’s strongest material!





Denchzk, Ritchie, Zettl, *et al*.

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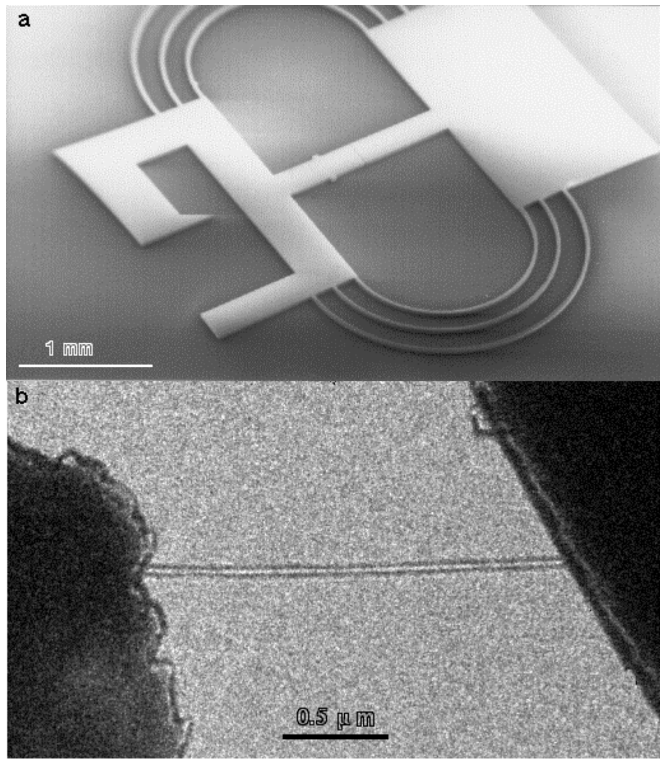
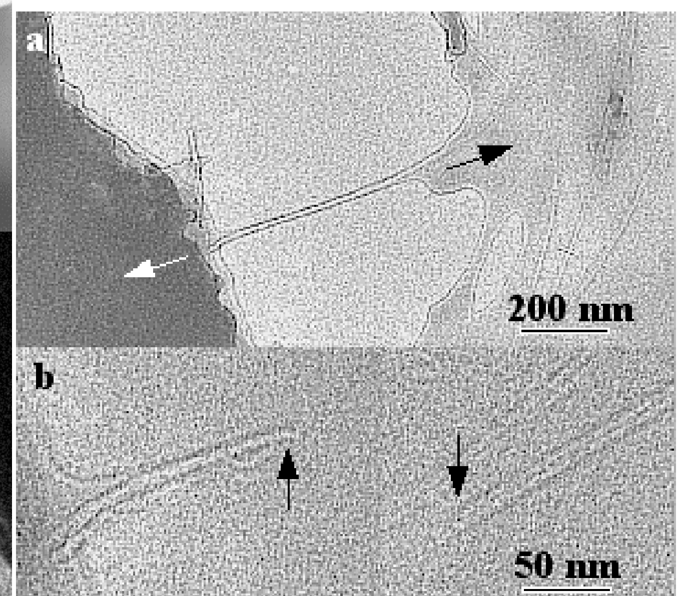
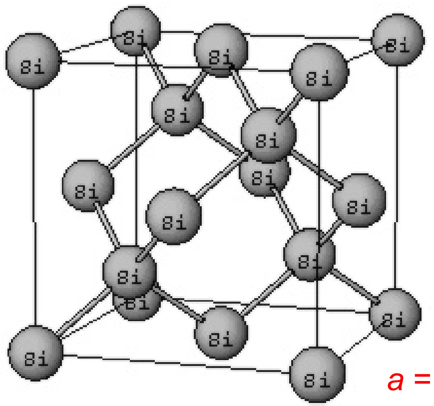




- Strength of the nanotube was measured as 150 GPa, i.e., roughly 5 times stronger than Kevlar or carbon fibers and more than 50 times stronger than hardened steel

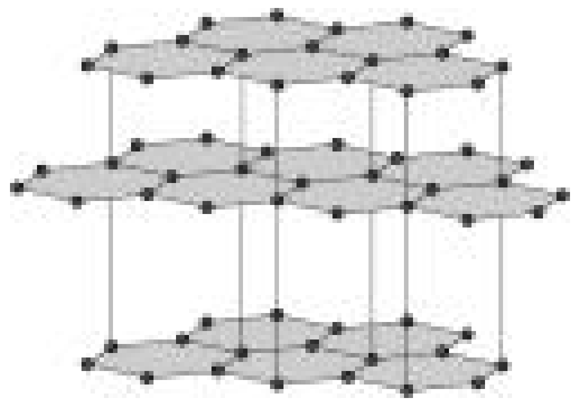
Alloptropic Forms of Carbon



a = 0.534 nm

diamond

- all strong (covalent) bonds

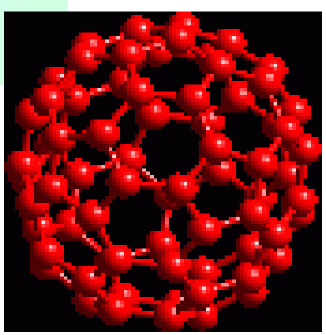


graphite

- strong bonds in layers
- weak (Van der Waals) bonds between layers

carbon C_{60}

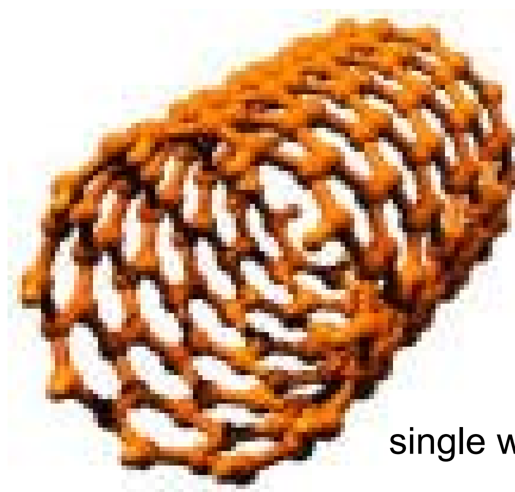
- all strong (covalent) bonds



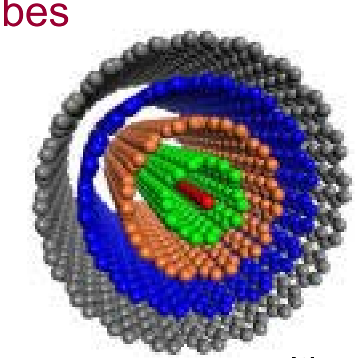
carbon C_{70}

carbon nanotubes

- strong bonds in tubes
- weak bonds between tubes

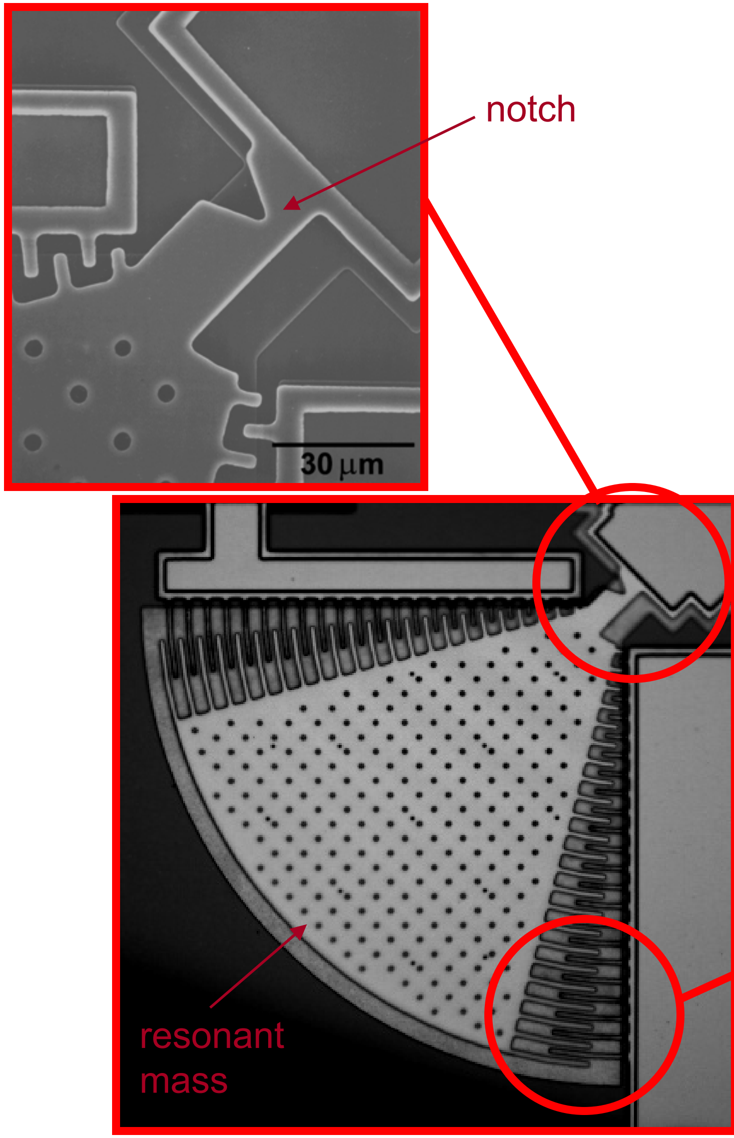


single wall

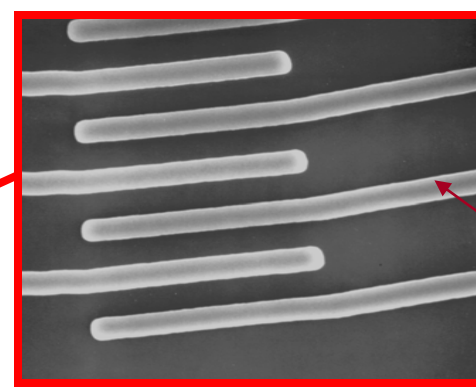


multi wall

Measurement of Fatigue Resistance



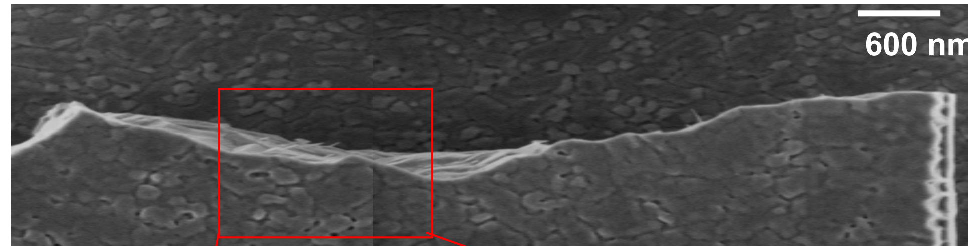
- notched cantilever beam attached to ~300 μm square perforated mass
- mass resonates at a frequency of 40 kHz, driven by “comb drives” on one side
- other side provides a means to measure displacements by capacitive sensing of motion; loads are computed numerically
- device is micro-fabricated from thin-film silicon (1 to 20 μm thick) with smallest notch root radius (1 – 1.5 μm) achieved by photolithographic masking

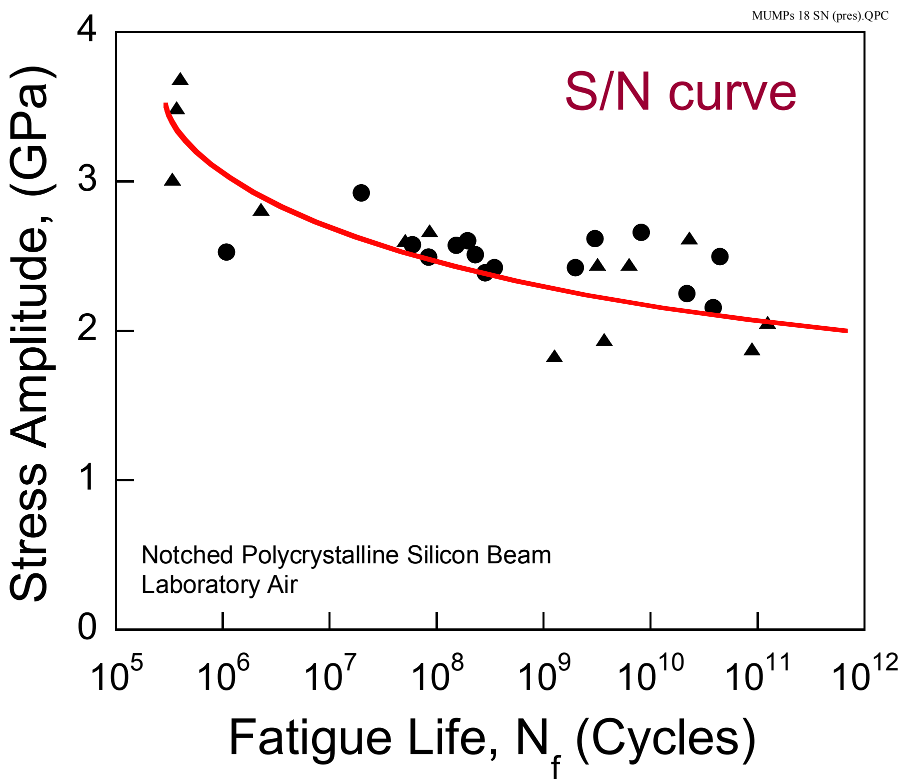


Brown, Van Arsdell, Muhlstein *et al.*

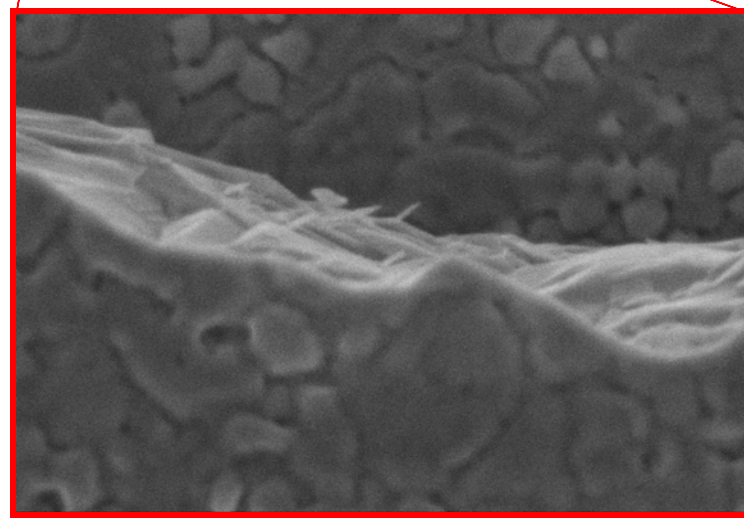
Fatigue of 2μm Polysilicon Films

- Micron-scale polycrystalline silicon films suffer delayed failure by fatigue
- Films can fail after 10^{10} cycles (3 days) at stresses of one half their fracture strength





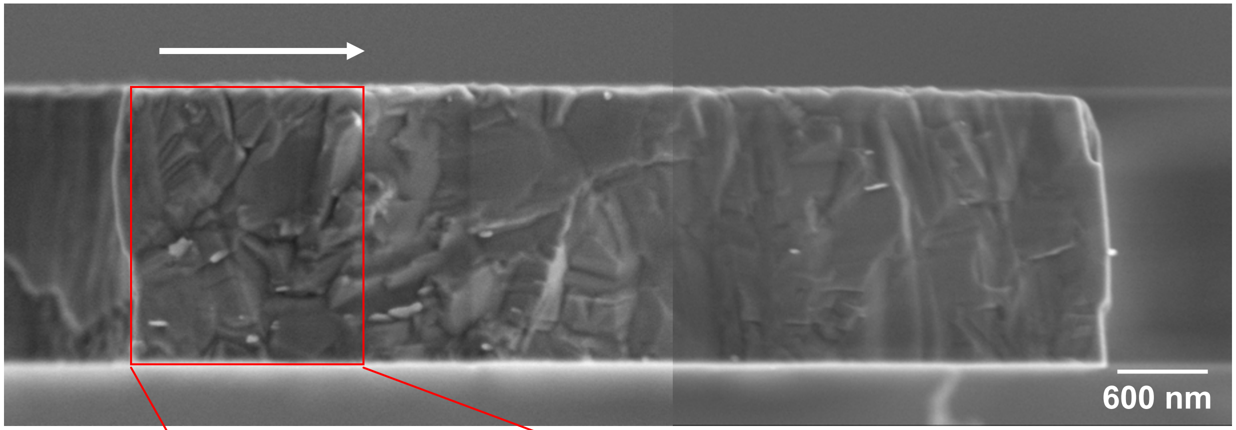
3.8 x 10^{10} cycles to failure



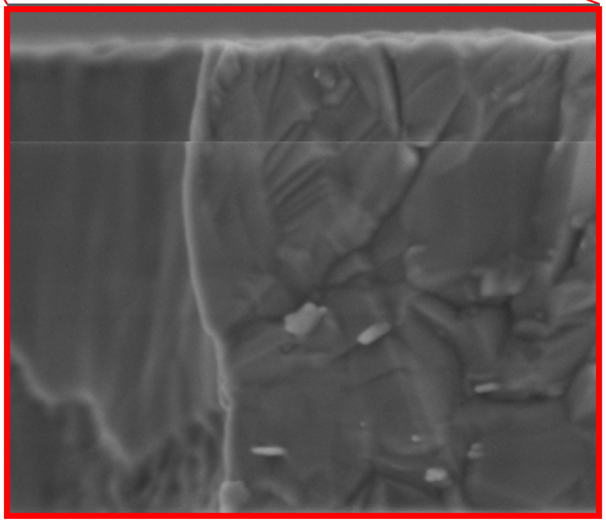
stress = load/area

Muhlstein, Brown, Ritchie, *Sensors & Actuators*, 2001

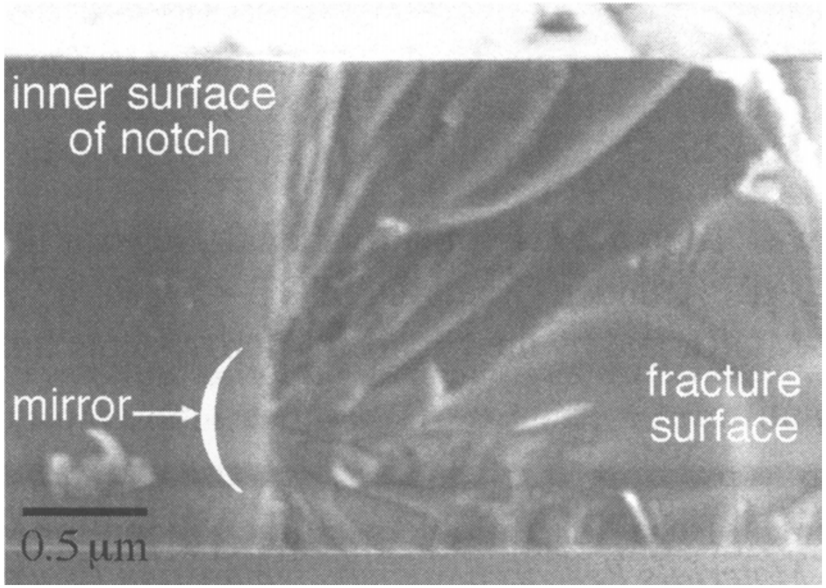
Fracture Surfaces of Silicon Films



cleavage fracture surfaces in silicon thin films



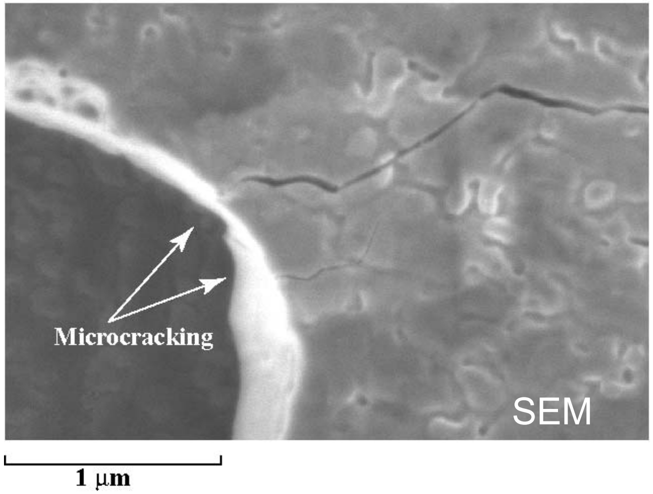
Muhlstein, Brown, Ritchie, *Sensors & Actuators,* 2001

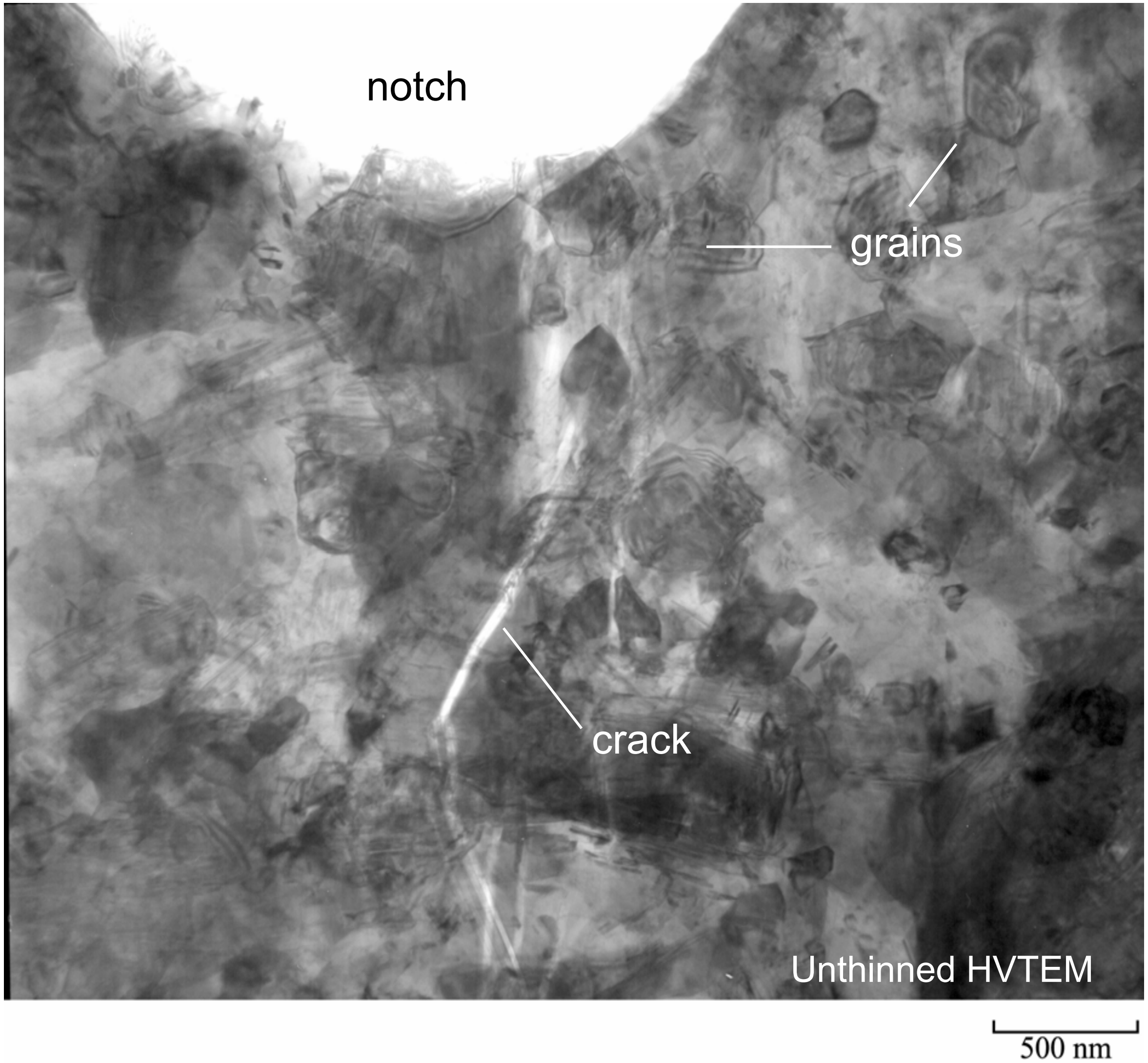


Ballarini *et al*., ASTM STP 1413, 2001

Transgranular Cleavage Fracture

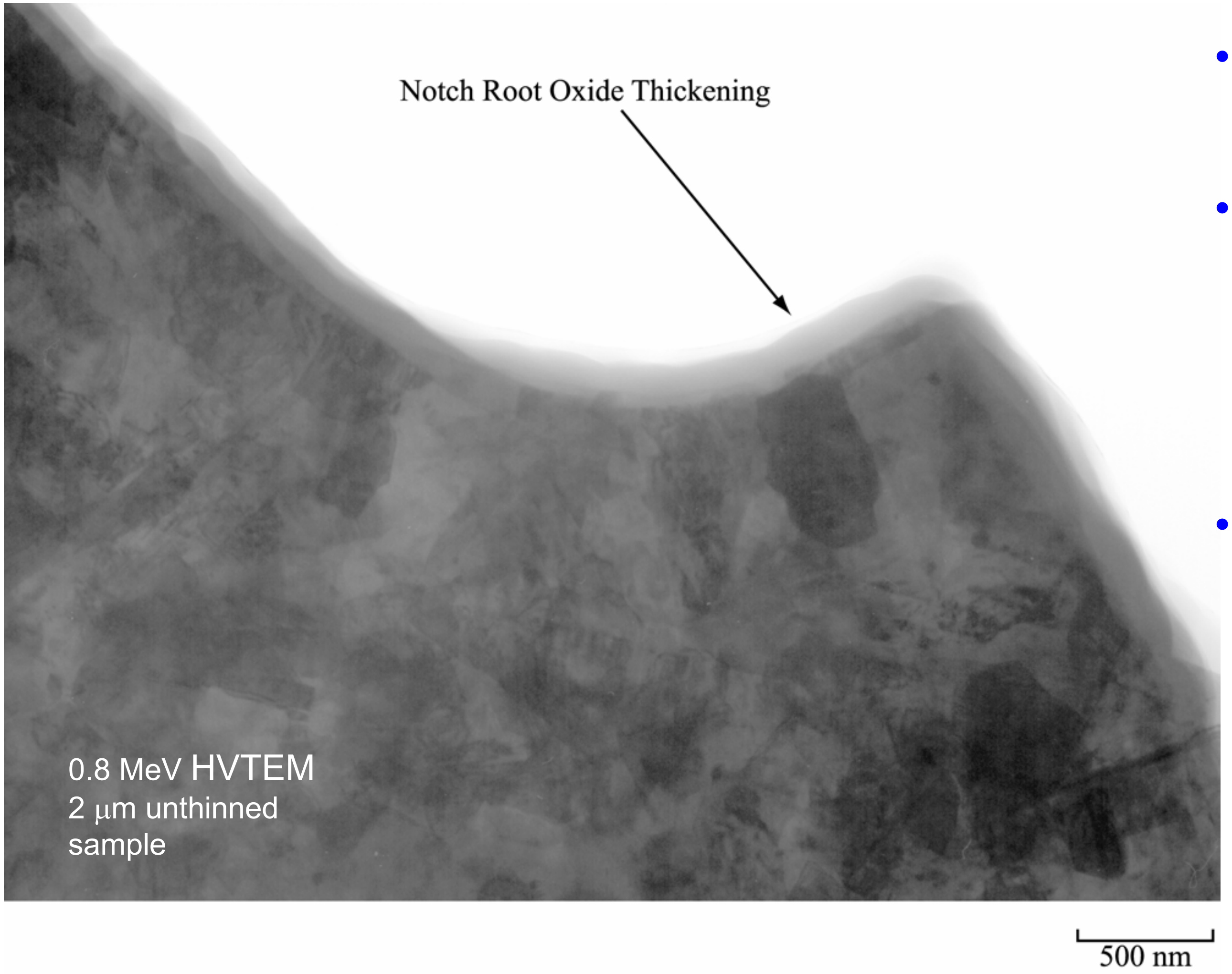
- transgranular cleavage cracking from notch through individual grains (crystals) showing the trajectory of the crack





Muhlstein, Stach, Ritchie, *Acta Mater.*, 2002

Notch Root Oxide Thickening



$N_f = 3.56 \times 10^9$ cycles

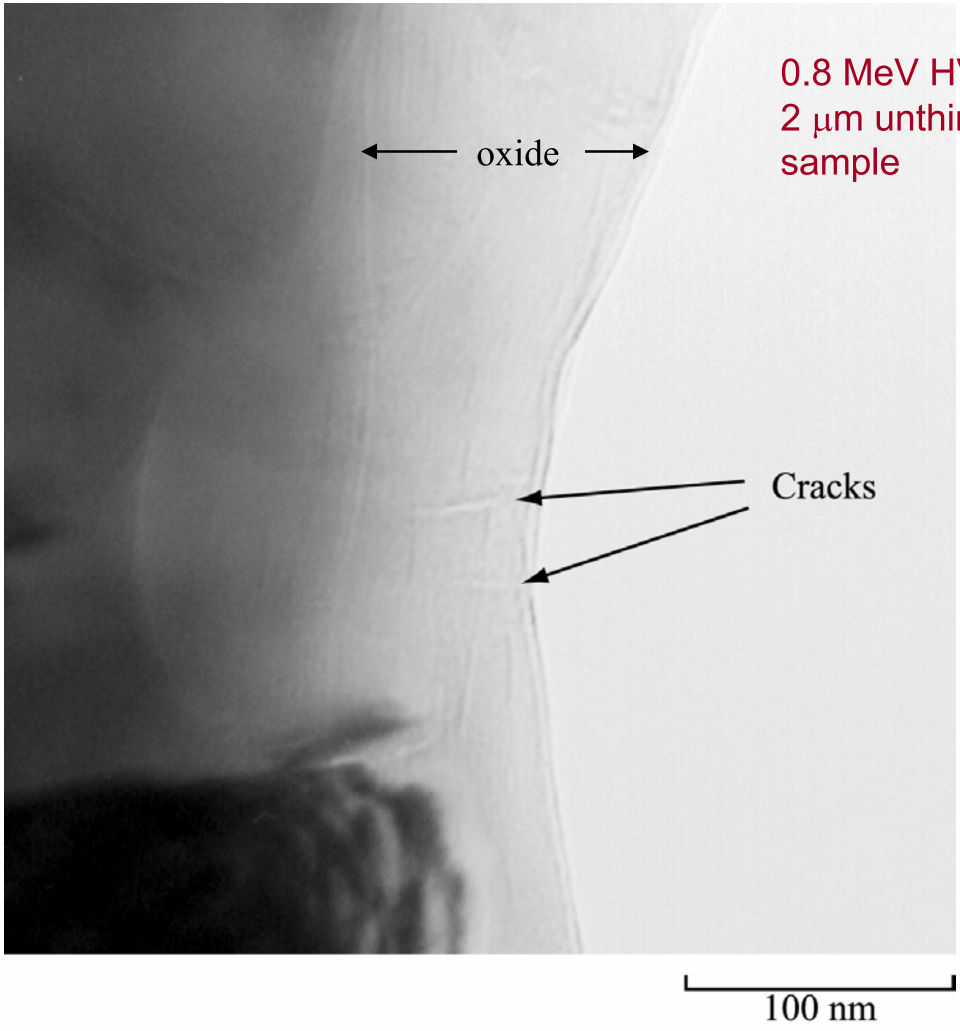
- native oxide thickness ~30 nm
- *in cyclic fatigue*, oxide thickness at notch root seen to thicken three-fold to ~100 nm
- *in sustained loading*, no such thickening is seen

Muhlstein, Stach, Ritchie, *Acta Mat.*, 2002

Cracking Occurs in Notch Root Oxide

- crack initiation in oxide scale during interrupted fatigue test
- evidence of several cracks ~40 – 50 nm in length
- the silicon oxide is a glass (amorphous) and is very sensitive to cracking induced by the presence of moisture (environmentally-assisted cracking)
- as the oxide layer is such a large fraction of the thin-film structure, a crack in this layer can cause failure of the whole device
- this does not occur in bulk Si

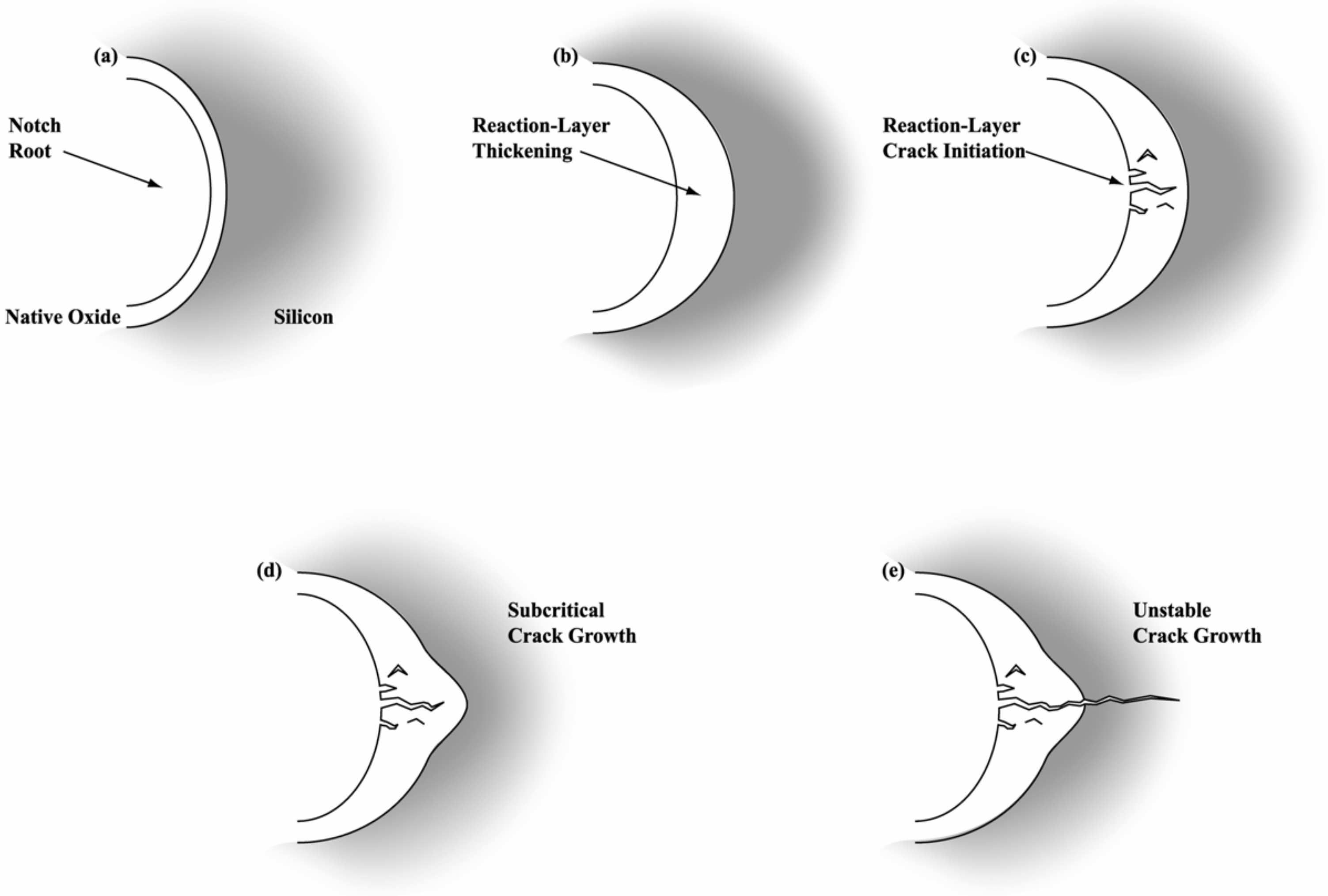
0.8 MeV HVTEM
2 μm unthinned sample



interrupted after 3.56×10^9 cycles

Muhlstein, Stach, Ritchie, *Acta Mater.*, 2002

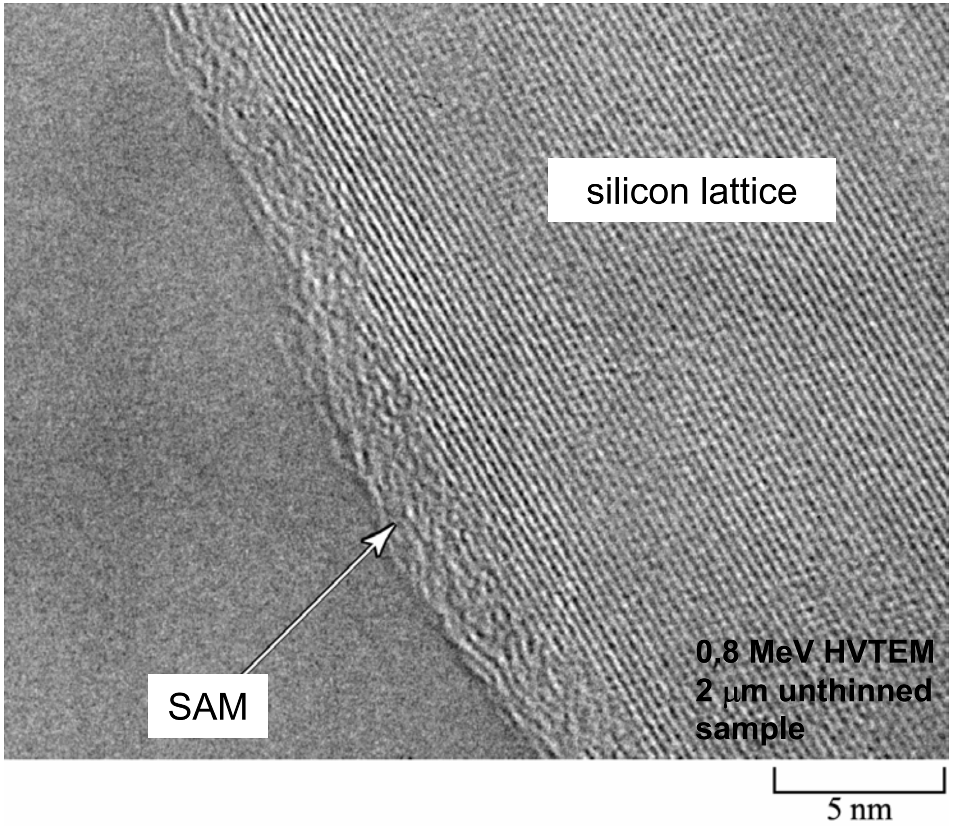
Fatigue Mechanism in Thin-Film Silicon

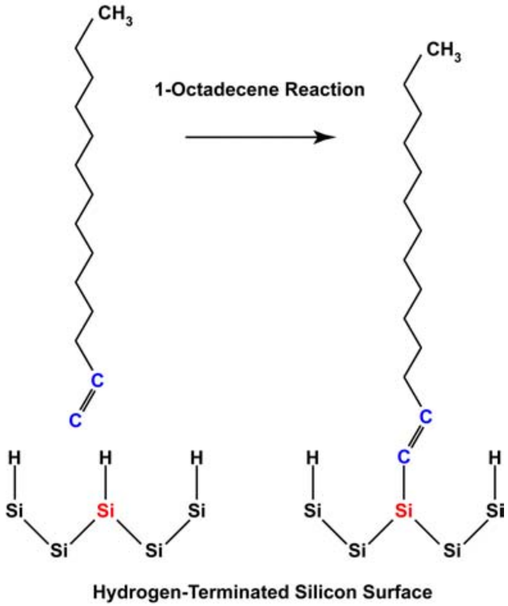


Muhlstein, Stach, Ritchie, *Appl. Phys. Lett.*, 2002

Self-Assembled Monolayer Coatings

- fatigue testing in the absence of oxide formation achieved through the application of aklene-based monolayer coatings

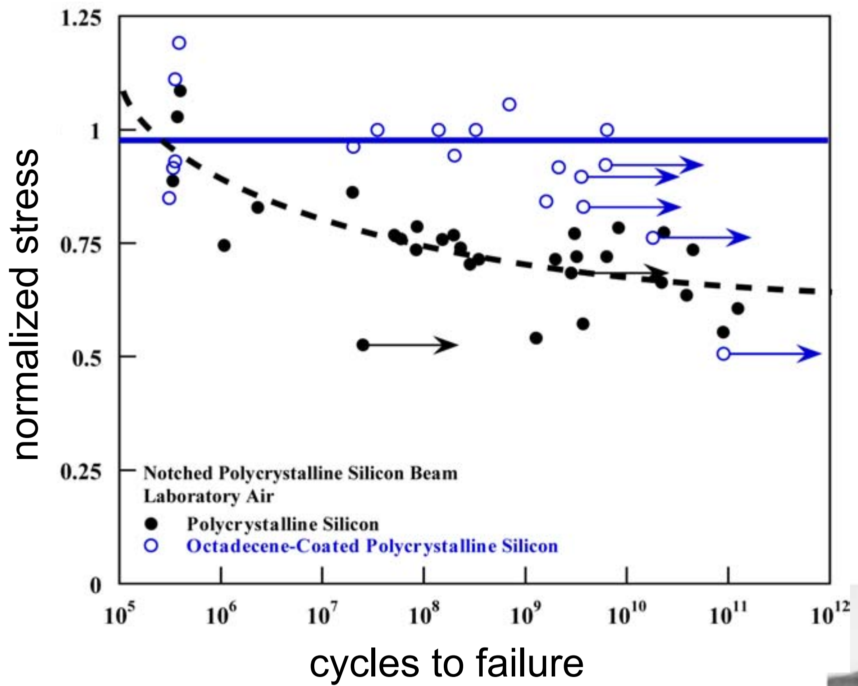




- Si chip is dipped in HF and then coated with alkene-based monolayer coating – *1-octadecene*
- alkene-based coating bonds directly to the H-terminated silicon surface
- coating is a few nm thick, hydrophobic, and stable up to 400°C; *providing a surface barrier to moisture and oxygen*

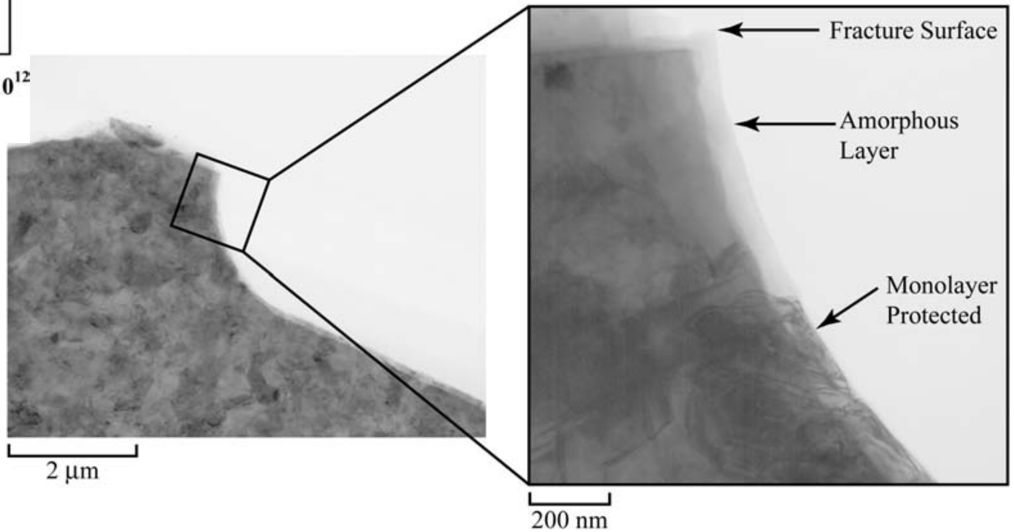
Muhlstein, Ashurst, Maboudian, Ritchie, 2001

Coated Samples are less prone to Fatigue



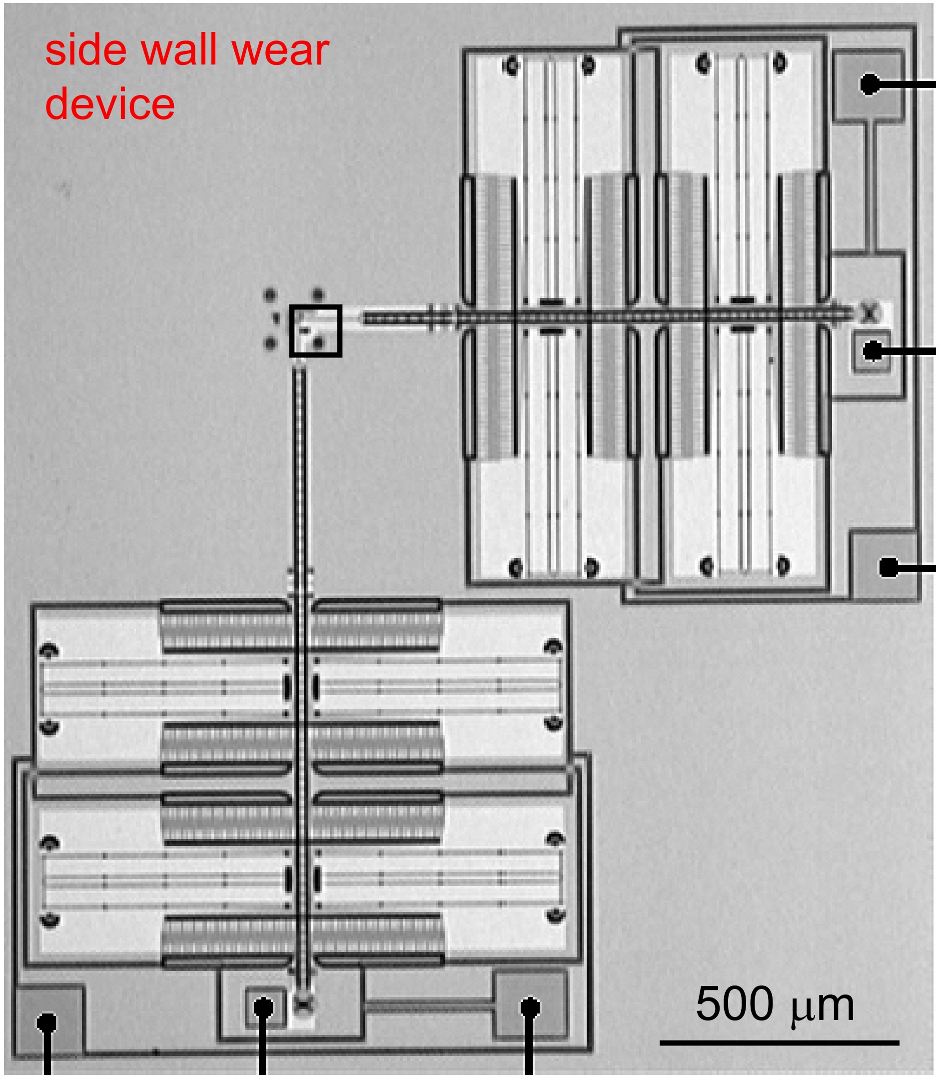
- SAM-coated Si samples display far reduced susceptibility to cyclic fatigue failure
- absence of oxide formation acts to prevent premature fatigue in Si-films

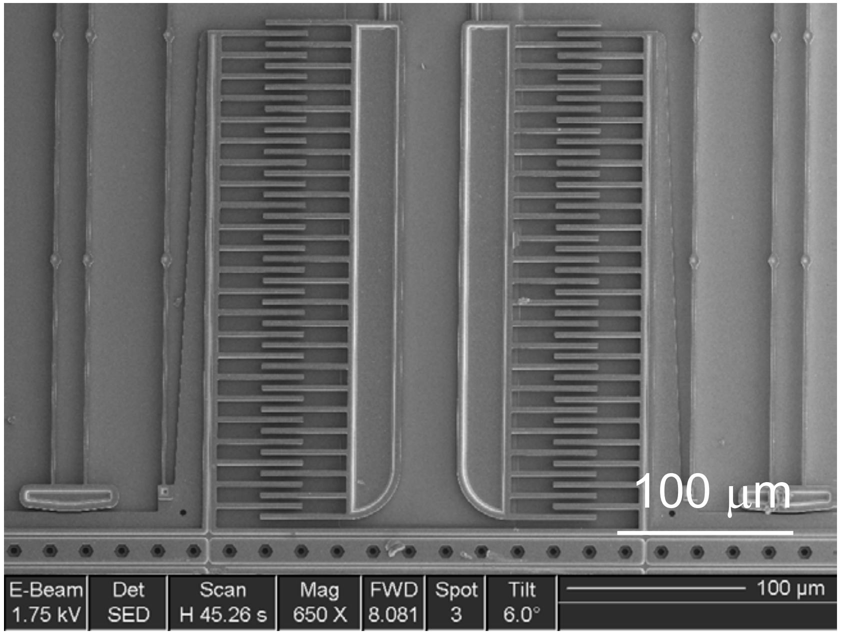
- alkene-based coatings, however, eventually wear out
- can also suppress such fatigue failure by operating your device in a vacuum



Muhlstein, Stach, Ritchie, *Acta Mat.*, 2002

Micro Device to Assess Wear



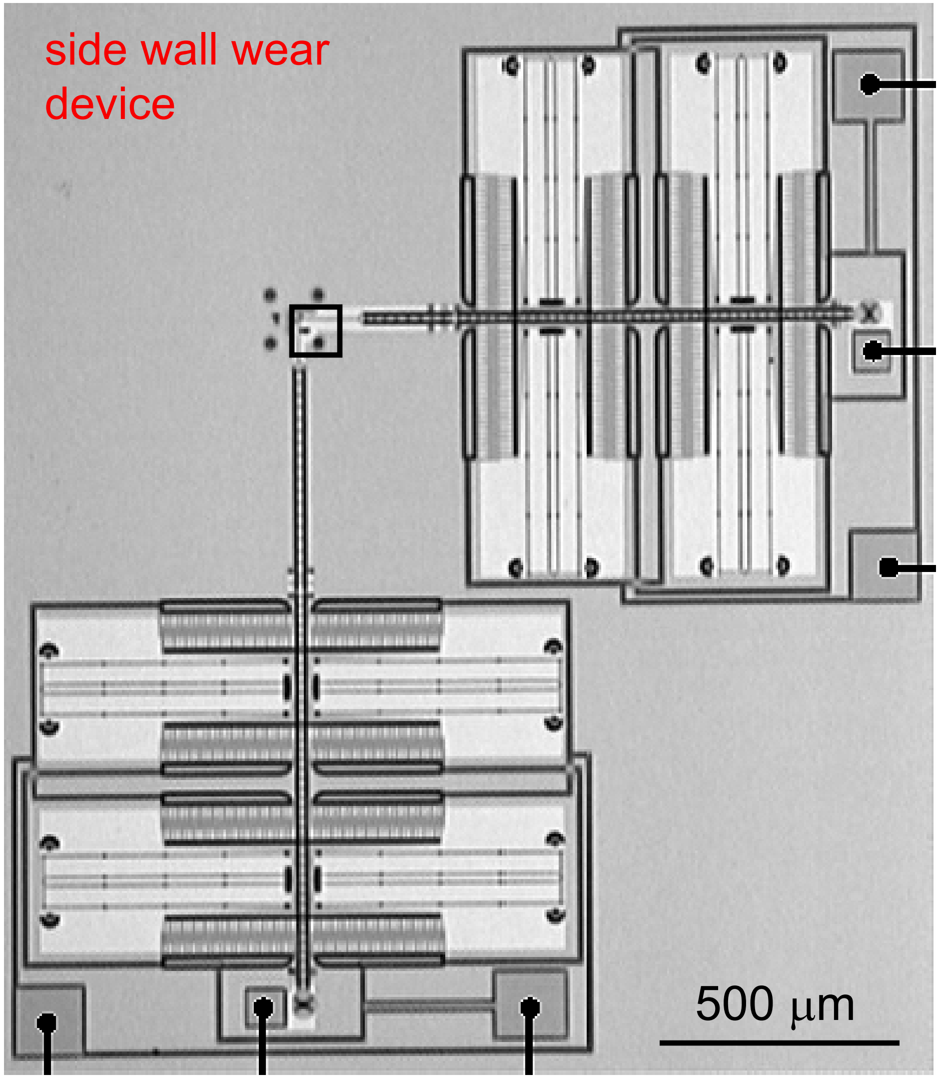


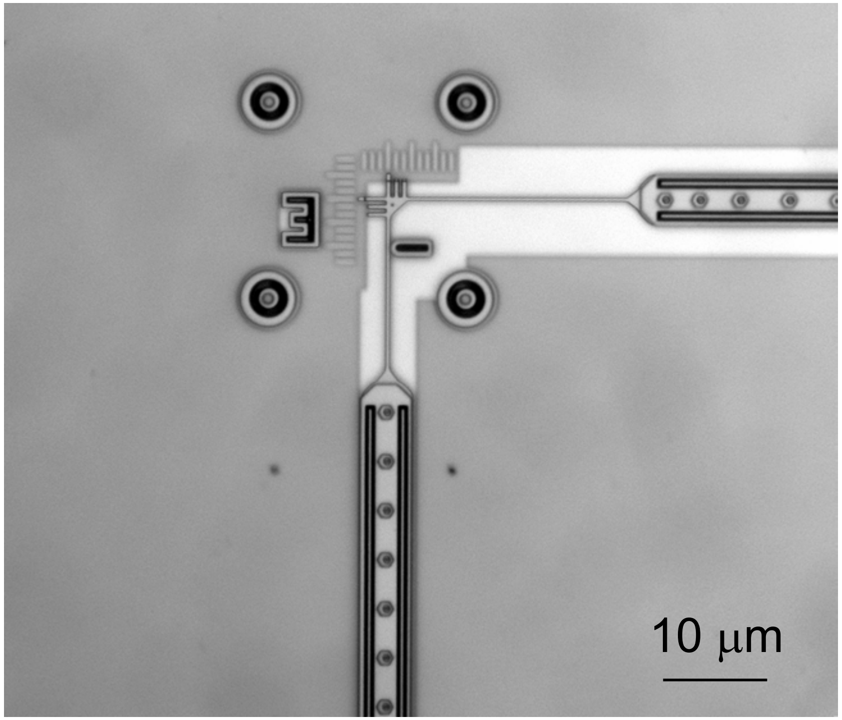
- electrostatically actuated using comb drives

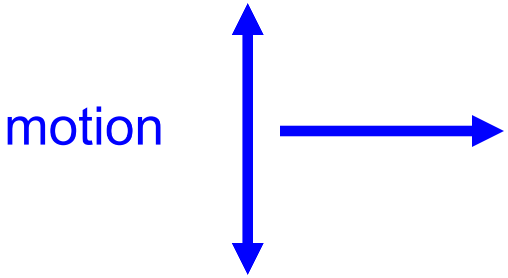
fabricated at the SUMMIT foundry at Sandia National Laboratory

Alsem, Dugger, Stach, Ritchie

Micro Device to Assess Wear

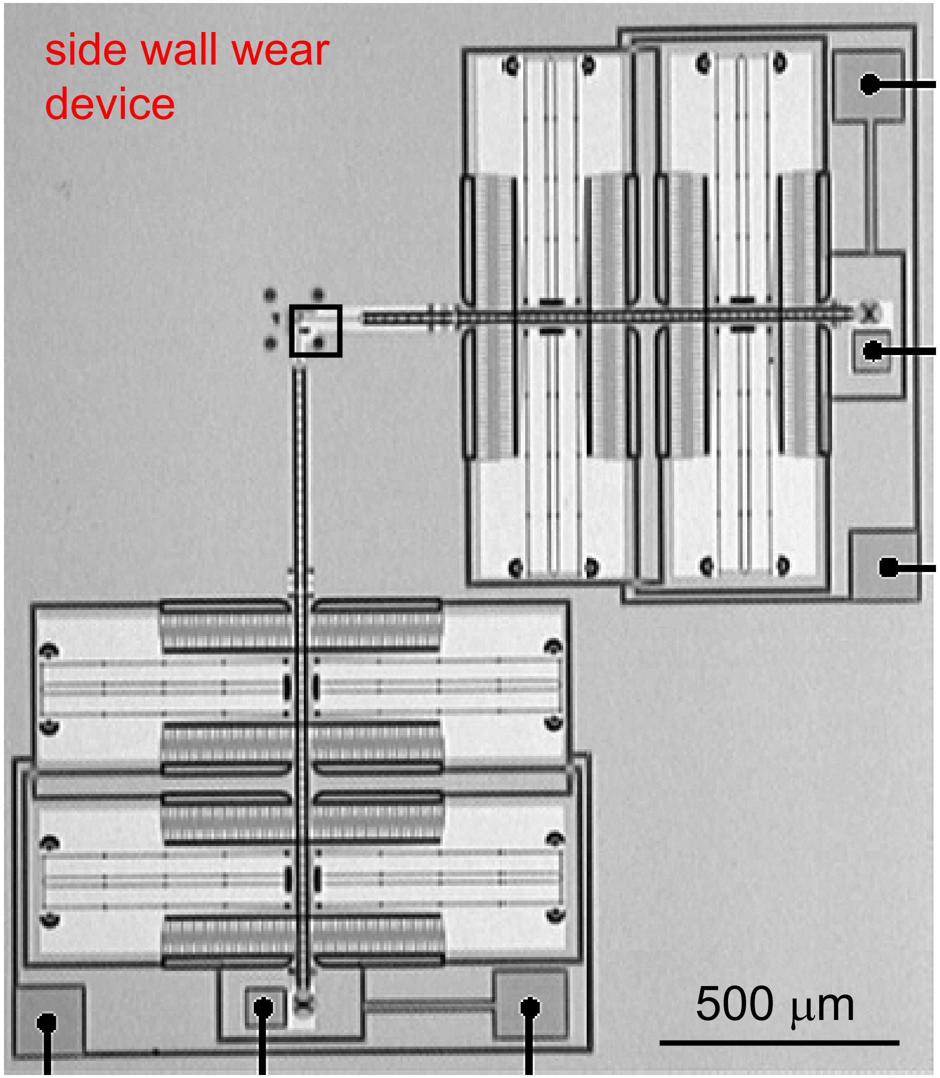


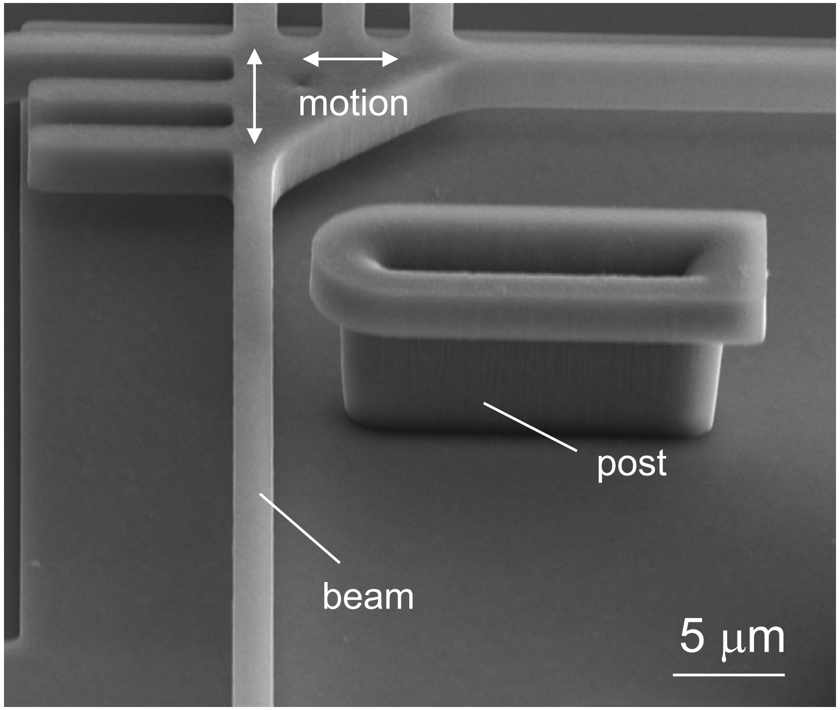




Alsem, Dugger, Stach, Ritchie

Micro Device to Assess Wear



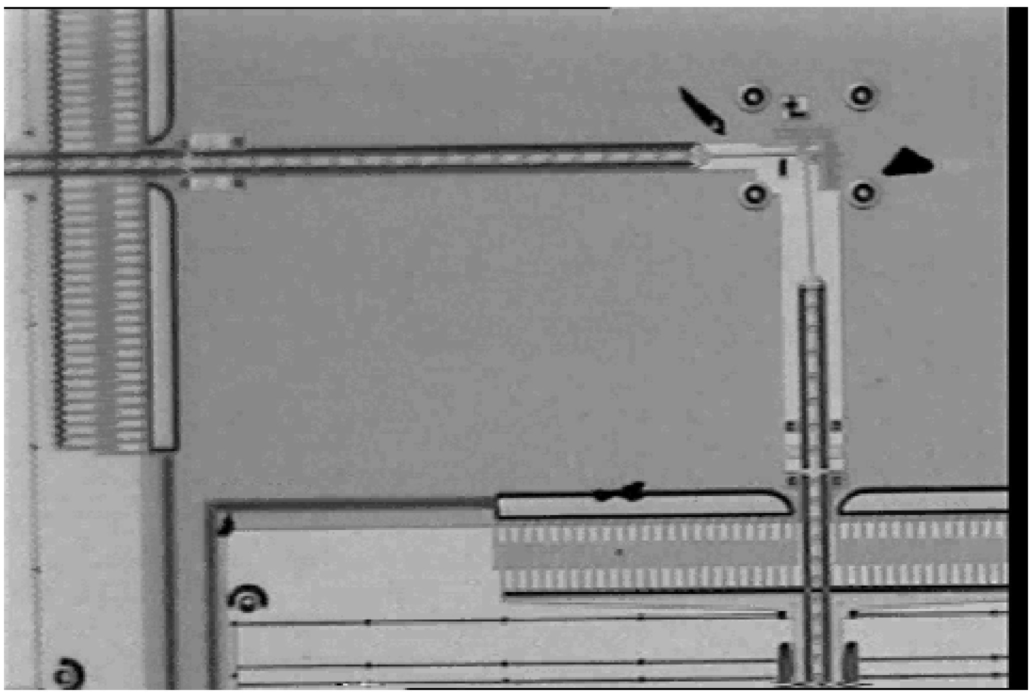


- sliding wear of beam on post

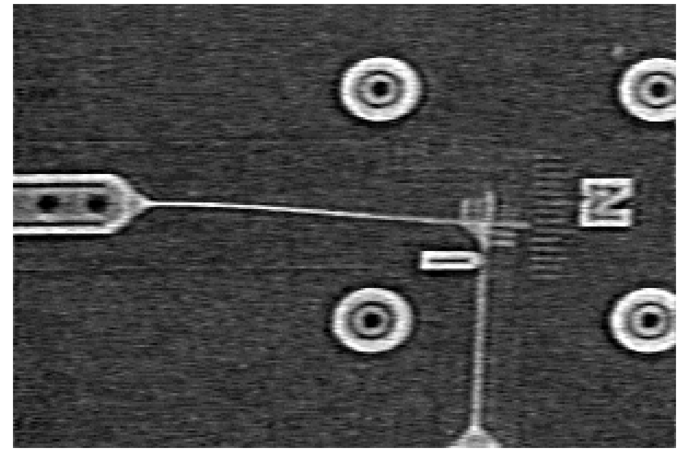
Alsem, Dugger, Stach, Ritchie

In Situ Measurement of Wear

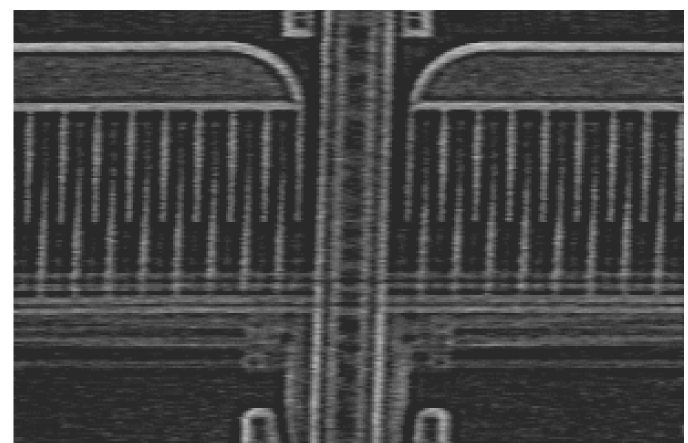
- Experimental set-up in motion to examine and measure the *in situ* wear properties inside the scanning electron microscope



500 µm



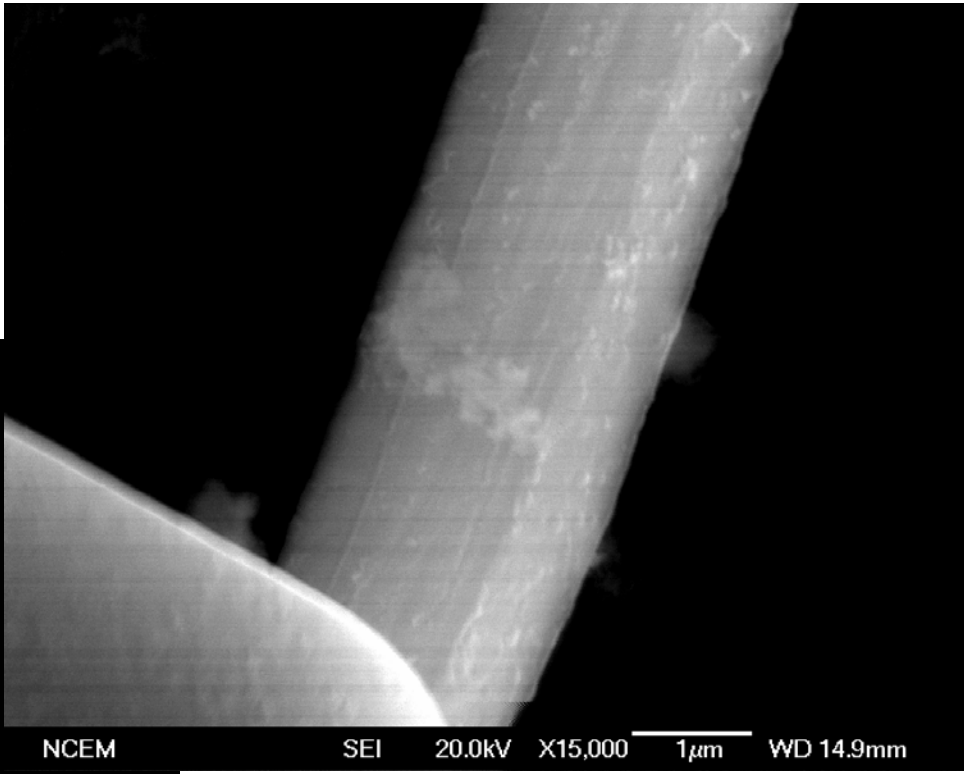
25 µm

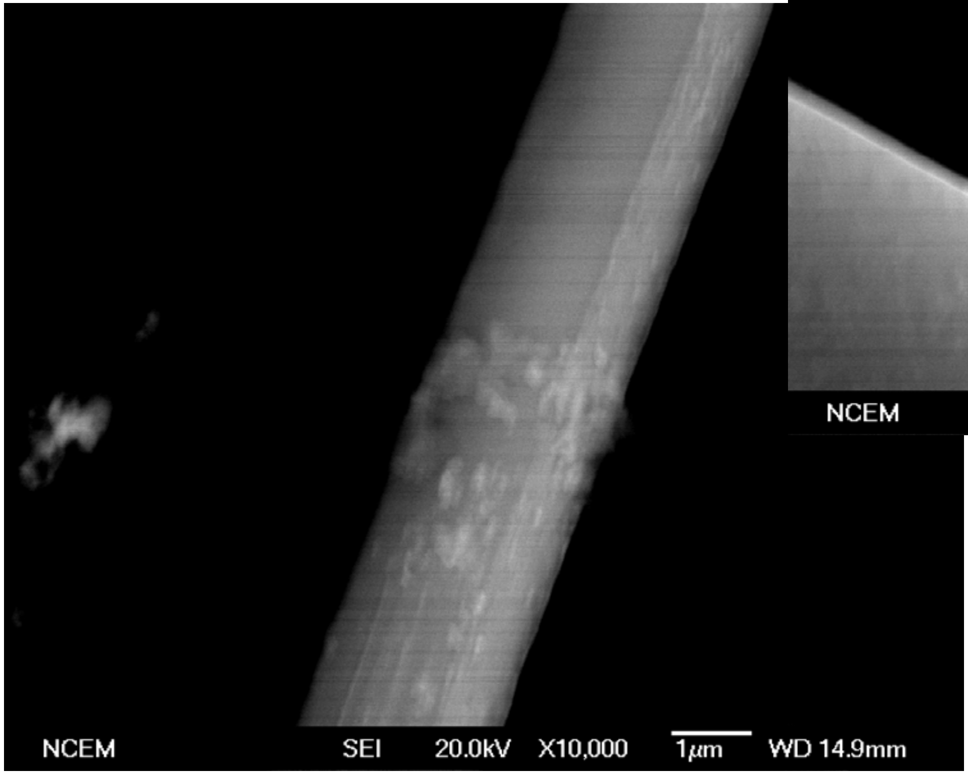


Alsem, Dugger, Stach, Ritchie

Wear Debris

- wear debris is analyzed in the TEM for its morphology and composition analysis





- *wear rate, K_w, is given by:*

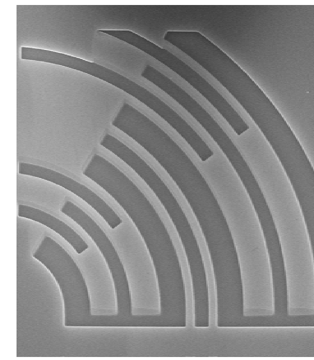
$$K_w = V_w/(P.S)$$

where V_w is the volume of material removed over a distance S under a load P

Alsem, Dugger, Stach, Ritchie

NEMS Mechanical Testing Device

- Nano-cantilever: fracture and fatigue at the nano-scale

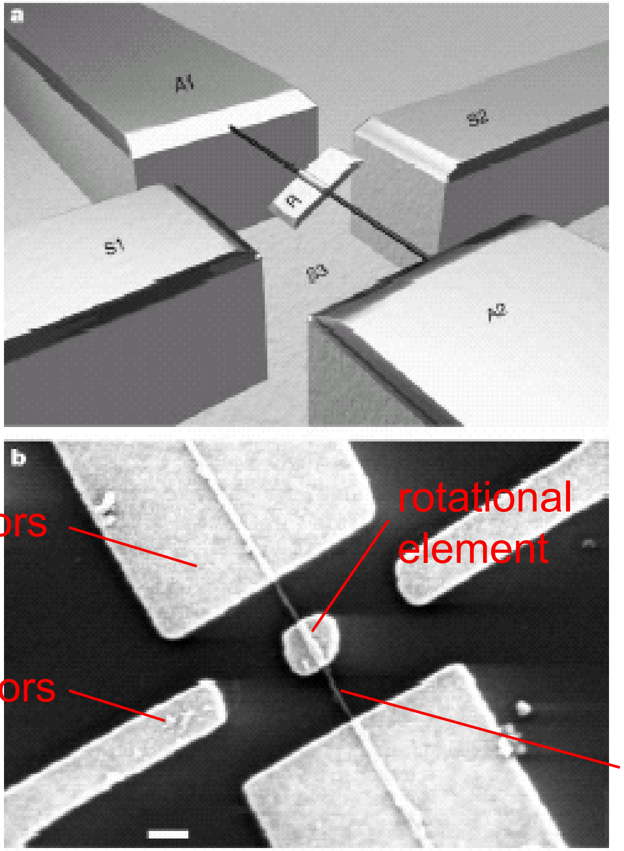


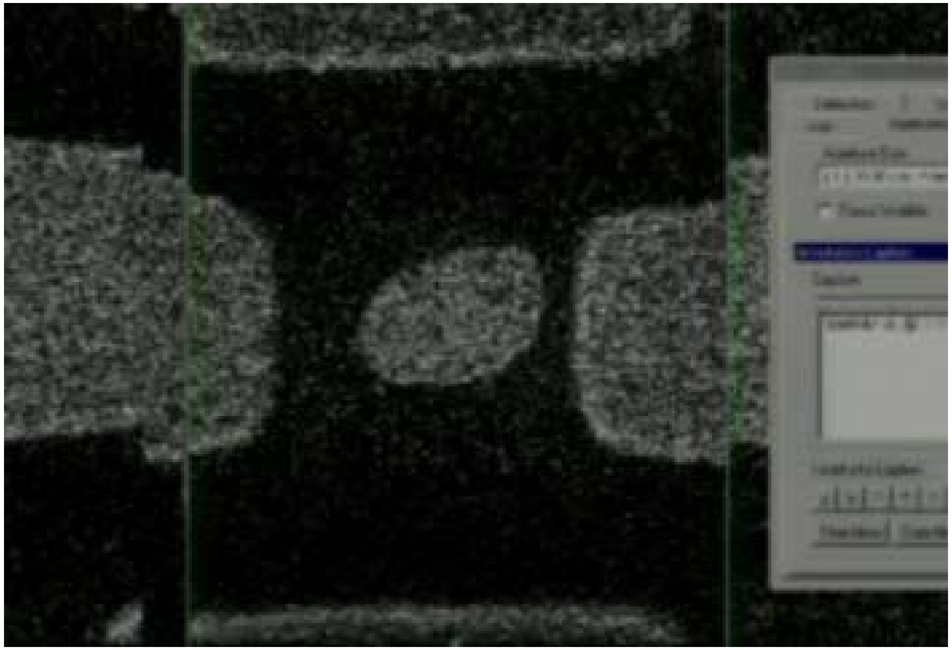
- smallest feature size ~20 nm; fabricated using a nanowriter from single crystal silicon

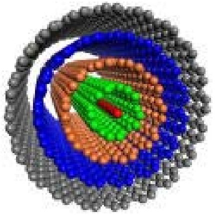
D-H.Alsem, E.A.Stach, J.A.Liddle, R.O.Ritchie

Electrostatic NEMS Nanomotor

- Alex Zettl, UC Berkeley, Physics Dept., July 2003



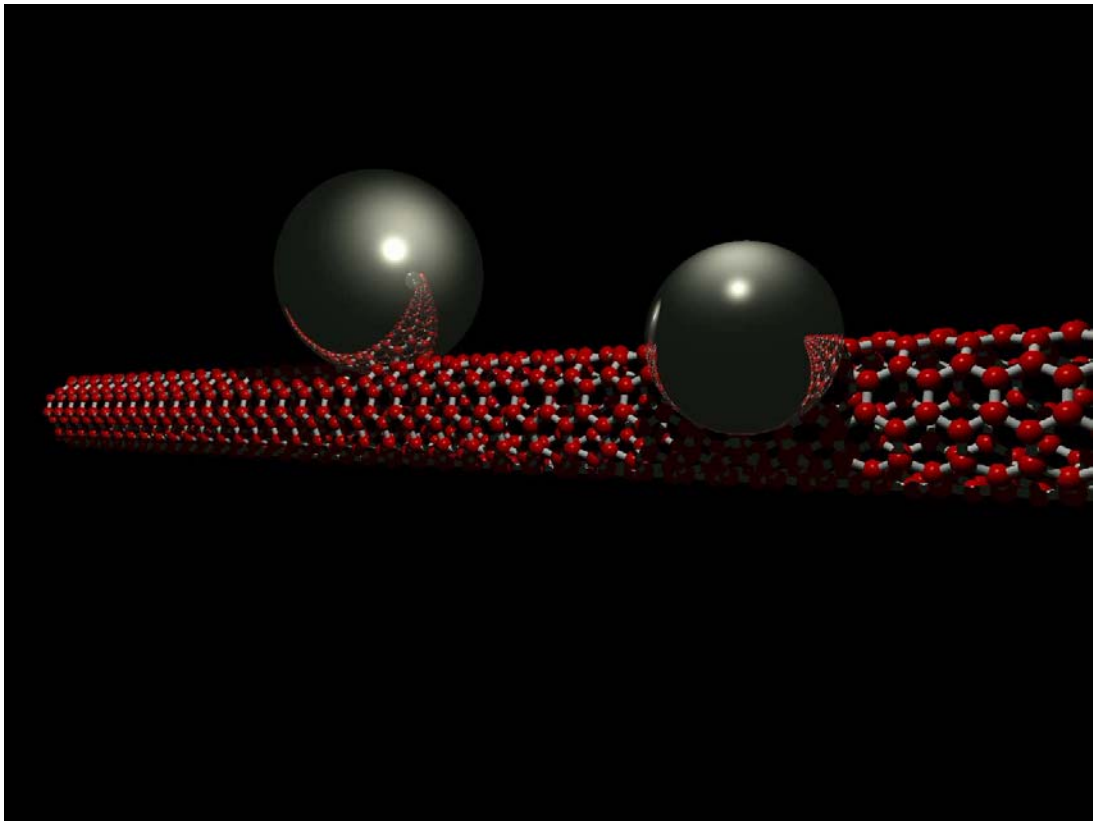




- device is nano-fabricated on a silicon chip and utilizes the rotary sleeve bearing characteristics of multi-walled carbon nanotubes

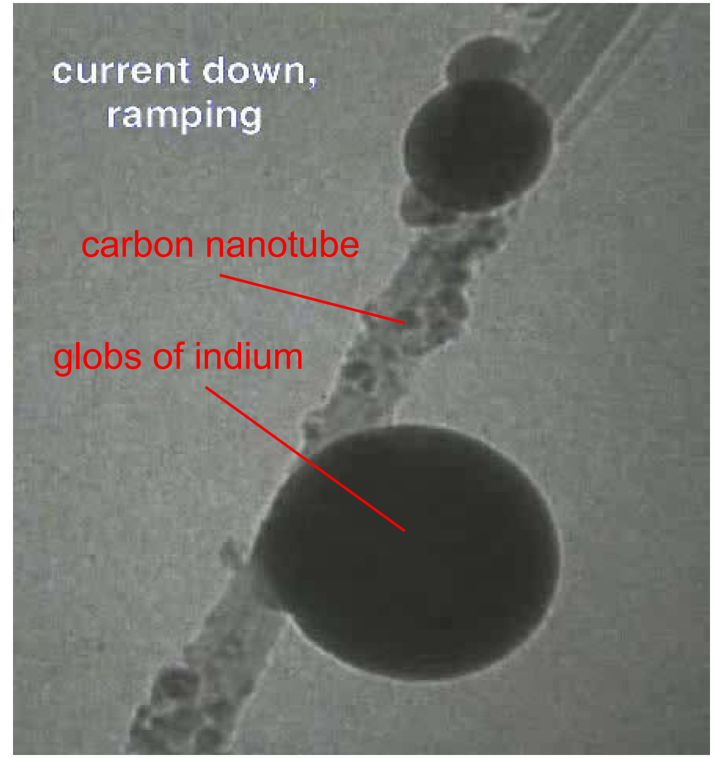
New Ideas for Nanomotors

- by reversing the electrical current along a carbon nanotube, we can move metal globs along the tube
- by putting the metal globs between two nanotubes, we can move then apart and do work



2 nm

animation



TEM image

5 nm

Be sure to see the next Nano*High lecture by Prof. Alex Zettl on such nano-machines!

Regan, Aloni, Ritchie, Dahmen, Zettl, *Nature*, 2004

Conclusions

- Micromachines or MEMS are playing an increasing role in our lives, whether as sensors for our automobiles, minute medical implant devices inside our bodies, or as weapons and tiny spies on the battlefield!

- The majority of MEMS are manufactured from silicon thin films using micro-fabrication techniques developed from integrated circuit IC technologies

- However, as silicon is such a brittle material, new micromachines will increasingly utilize other materials, including ceramics such as silicon carbide, metals such as nickel, and shape-memory materials such a Nitinol

- In research, these machines are critical for probing the properties of materials at increasingly smaller dimensions

- Current research and future developments will shrink these machines even further, i.e., to the nanoscale – NEMS – although the vast majority of such devices are still in the realm of scientific/engineering research.

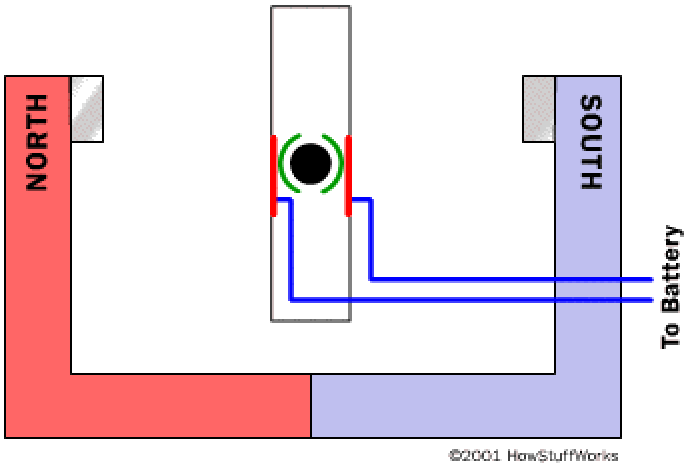
Acknowledgements

Useful links and thanks due to:

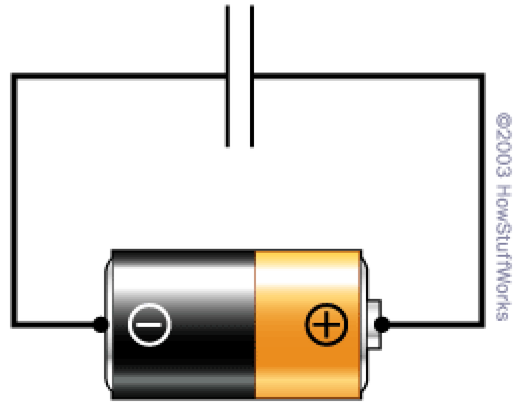
- My research group, especially Daan Hein Alsem (http://www.lbl.gov/Ritchie.htm)
- My colleagues & former students, especially Tony Tomsia, Eric Stach, Andy Minor (NCEM) (http://ncem.lbl.gov/frames/center.htm) & Chris Muhlstein (Penn State)
- UC Berkeley BSAC web page, especially Elliot Hui's "Overview of MEMS" (http://w-bsac.eecs.berkeley.edu)
- UC Berkeley EE245 lecture notes by Roger Howe & Thara Srinivasan (http://www-bsac.eecs.berkeley.edu/projects/ee245/index.htm)
- Sandia National Laboratory web page (http://mems.sandia.gov/scripts/index.asp)
- University of Colorado at Boulder "CU MEMS web", especially Adrian Michalicek's "Introduction to MEMS" (http://mems.colorado.edu/c1.gen.intro)
- David Johnson & Leticia Menchaca of the TiAl Alloy Company (http://www.tinialloy.com)
- Tom Duerig & Alan Pelton of Nitinol Devices & Components (NDC) (http://www.nitinol.com)
- Chris Regan & Alex Zettl's Group in UC Berkeley Physics (http://www.physics.berkeley.edu/research/zettl)
- and finally research support from the U.S. Department of Energy, NEDO, Exponent & NDC.

from http://science.howstuffworks.com

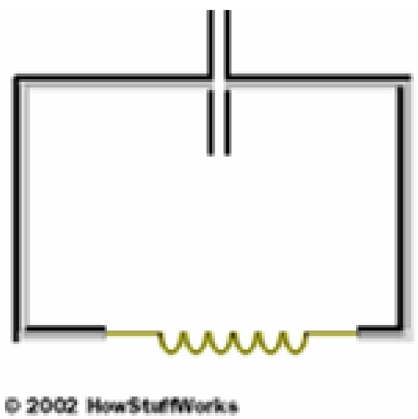
Electric motor



Capacitor



Oscillator



Inductor